PHOTOGRAMMETRIC ANALYSIS OF TRAFFIC FLOW CHARACTERISTICS ON MULTILANE HIGHWAYS

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by

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PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

PHOTOGRAMMETRIC ANALYSIS OF TRAFFIC FLOW

CHARACTERISTICS ON MULTILANE HIGHWAYS

TO: K. B. Woods, Director
Joint Highway Research Project

May 15, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File No: [illegible]
Project No: C-36-[illegible]

Attached is a Final Report entitled "Photogrammetric Analysis of Traffic Flow Characteristics on Multilane Highways" by Mr. William F Howes, Graduate Assistant on our staff. The research reported was performed under the direction of Professor R. D. Miles. Mr. Howes also used the [illegible] as his thesis for his degree of Master of Science in Civil Engineering.

The research reported is [illegible] an evaluation of the use of aerial photographs for the measurement of characteristics of flow of vehicular traffic. The results of the study were summarized in a paper which was presented at the [illegible] Purdue Road School.

The report is [illegible] rec[illegible]

[illegible] submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:bc

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Final Report

PHOTOGRAMMETRIC ANALYSIS OF TRAFFIC FLOW CHARACTERISTICS ON MULTILANE HIGHWAYS

by

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File No: 1-4-19

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Lafayette, Indiana

May 15, 1963

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The author has drawn freely upon the talents and experiences of many individuals. Professor Robert D. Miles, Research Engineer with the Joint Highway Research Project, guided the author throughout the study. Professor Harold L. Michael, Associate Director of J.H.R.P., assisted with the traffic engineering phase of the research, and Dr. Irving W. Burr and Mr. R. L. Conn of the Department of Statistics advised on statistical questions.

Aerial photography for the study was secured through the efforts of Messrs. D. H. Payne, N. L. Smalley, Dean Timmerman and Elmer Pohle of the Bureau of Photogrammetric and Electronic Processes, Indiana State Highway Commission.

For their drafting services and assistance in reducing the traffic data, the author is particularly grateful to Messrs. M. V. Ali, L. B. Anderson, M. R. Carr, H. M. Cassiday, D. W. Deno, J. L. McWhinney, D. W. Mueller, R. L. Williams and D. R. Wilson.

All illustrations were prepared with the aid of Mr. E. L. Black and Mr. M. R. Carr. Typing of the manuscript was in the capable hands of Mrs. Loeda Cassiday and Mrs. Virginia Cunningham.

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ABSTRACT

Howes, William F., MSCE Purdue University, June 1963. Photogrammetric Analysis of Traffic Flow Characteristics on Multilane Highways. Major Professor: Robert D. Miles.

This research explored the applicability of various aerial photography techniques to the collection and analysis of highway traffic flow data. Specifically, time-lapse and continuous strip aerial photographs were investigated relative to their accuracy and efficiency in securing speed, volume, headway and other pertinent information for multilane highway facilities. The results were then compared with conventional ground techniques, as represented by a pneumatic tube-graphic recorder system.

The aerial photography method, although impractical for the conventional fixed location traffic survey (e.g. a volume count or spot speed study), demonstrated a significant potential in the task of recording traffic phenomena over "space" as well as time. Time-lapse photography, with its ability to record a given driver's behavior in a series of exposures, was judged to be the most accurate and practical way to analyze acceleration, merging, diverging, weaving and passing patterns over extended lengths of the study route.

These are important traffic flow characteristics which are all but impossible to study by automatic ground methods.

Stereo continuous strip photography, although lacking the time-lapse technique's proficiency at "tracking" vehicle movements, represents, nevertheless, a valuable means of collecting speed, volume and headway data at a large number of sites concurrently.

Among the most important assets of the aerial photographic method is its ability to pictorially record the environment in which traffic data are obtained. This attribute enhances the value of the data by affording the investigator possible reasons for unusual traffic behavior. The aerial photographs also serve as a detailed and visual inventory of the route's condition, control devices and surrounding culture.

Several speed-volume-headway-density relationships were developed for the sites investigated. However these were all based upon a limited amount of data and, therefore, were not considered conclusive.

INTRODUCTION

The Question

In the course of the next ten years more than thirty billion dollars will be spent at the federal, state and local levels for the construction of new roadways in the United States. Countless billions more will be allocated for the rehabilitation and maintenance of existing facilities.

The thoughtful observer might well question to what end is this huge expenditure being made. Highway officials claim that it is to promote the efficient flow of the Nation's goods and populations. But what assurance do we have that this program will actually foster efficiency in transportation. A frank reply would have to be, "Very little, indeed!"

The Problem

Remarkably little is known about the flow patterns of motor vehicles on the highway. Although a voluminous amount of traffic data has been collected since the earliest days of the automobile, nearly all of it stems from special purpose surveys which offer little insight into to the

actual physical and psychological nature of traffic flow. Investigators have dealt at length with volume counts, spot speed studies, travel time determinations, vehicle spacing measurements, etc., as singular phenomena, rarely attempting to seek possible relationships between these various elements of traffic flow. An understanding of complex flow characteristics demands a multipurpose investigation in which data on all the pertinent factors are collected and analyzed. This monumental task will undoubtedly require new and improved information gathering techniques.

Notable exceptions to the tradition of single purpose traffic surveys were the route capacity studies conducted by the Bureau of Public Roads in the 1930's and 1940's (65, 13)* and summarized with the publication of the Highway Capacity Manual in 1950 (13). However, even this valuable reference is saddled with a serious drawback - it is outdated. Motor vehicles of the '30's and '40's bear little resemblance to today's models. Likewise, driver behavior and road quality have undergone significant changes. An observer could hardly expect to witness the same flow characteristics on today's freeways as he might have on the highways of just two or three decades ago.

It is only within a framework of current traffic data that one can hope to advance meaningful solutions to present traffic problems. It is, therefore, acknowledged that the

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* Numbers in parentheses refer to bibliography.

mere development of improved survey techniques is not enough. The methods evolved must also be so efficient that they actually promote the continual updating of traffic data.

Numerous attempts have been made in recent years to develop theories relating the various elements of traffic movement and, by means of mathematical models, to apply these factors to route capacity determination and to design and control criteria. A brief consideration of these flow concepts indicates the data requirements facing present investigators.

There are five common approaches to the study of traffic flow characteristics: statistical, analogy, car-following, queueing theory, and simulation. Most studies to date have employed statistical methods and have been empirical in design. Adams (1) noted that vehicle placement on the highway takes the form of a random series and can be approximately described by the Poisson distribution for random events. Others (19, 27, 40, 53, 55) have derived modifications to the Poisson which permit a closer fit to field data. A Gaussian distribution for accelerations was suggested by Montrol (62), while Oliver (66) and Wardrop (82) have presented theoretical distributions for gaps and speeds respectively. Speed, spacing, density and volume interrelationships have been analyzed from field data by Greenshields (34, 35, 36, 39), Norman and Walker (65, 13), Forbes (21), Glanville (29), May (61), and Wagner and May (79).

The dynamics of high density traffic flow in a single lane with passing prohibited has been treated as a continuous fluid by Prager (70), Lighthill and Whitham (56), Richards (74), Greenberg (32), and Greenberg and Daou (33). A rarefied gas analogy, in which molecules represent vehicles, was used by Newell (64) in applying kinematic theory to the behavior of low traffic volumes. The kinetic theory of gases was drawn upon in the development of a Boltzman-like speed distribution equation by Prigogine and others (3, 71, 72).

A deterministic approach has been employed in theories on car-following dynamics. A line of traffic with no passing was treated as a servomechanism by Pipes (68, 69), and the theory has been expanded upon by other investigators (11, 12, 25, 43, 44, 45, 54).

The application of queueing theory to highway traffic was suggested by Beckman, McGuire and Winsten (5), Haight (42) and Miller (61). Gerlough and Mathewson (28), Gerlough (26), Goode (30), Helly (43), and Lewis (55) have reported on the use of digital computers for solving complex traffic problems through the simulation of vehicle and driver behavior.

Most of these theories are still in the fledgling stage. Many, bedecked in simplifying assumptions, describe only ideal situations and, therefore, find very limited application.

The further development of each is being hampered by a critical lack of appropriate field data. Existing data have

generally been obtained at a fixed "spot" location on the study route and over a finite period of time. The various concepts of traffic flow suggest, however, that information collected over "space" as well as time would be far more useful. This, of course, places new and more challenging demands on data collection technology.

A REVIEW OF DATA GATHERING METHODS

Paralleling the rapid development of the automobile has been the advancing technology of traffic data gathering devices. Although most techniques were originally designed to fulfill a specific need at a given time and location, a few were eventually standardized and find many and varied applications.

It is useful to classify data collection methods into two broad functional categories. Those which operate over a specified time period but only at a narrowly defined location on the highway will be referred to as "time-spot" methods, while those collecting over both time and a substantial length of roadway will be denoted as "time-space" methods. Nearly all methods, irrespective of classification, are characterized by three components: a sensing or detecting device, a recording mechanism and one or more associated data reduction techniques.

Manual Methods

In recent years the sensing, recording and data reduction methods have assumed many guises. The simplest, and frequently most rapid and accurate, techniques are the

numerous manual methods (4, 48, 57). Manual operations, most of which are "time-spot" in character, are commonly employed in volume counts, spot-speed surveys (4), volume-density (75) and license plate (81) determinations of travel time, and the measurement of judgment and perception time in passing (20). With the exception of ground movies, observer or interview methods are the only practical ways to determine vehicle occupancy. Classification of vehicles by type and intersection turning movements may also be most accurately accomplished manually.

For large scale surveys, however, these techniques are prohibitively time consuming, require an excessive field labor force, may be impeded by bad weather, and are difficult to render obscure to the motorists (8, 63, 84).

Moving Vehicle Methods

Recent years have witnessed considerable interest in moving vehicle "time-space" methods for determining route volume, average speed, and travel time. Two basic techniques have been developed: the "floating car" (57, 81) and the "average car" (4, 38, 81). Although both employ the "test run" concept, the "floating car" procedure requires that the driver pass a vehicle for each one passing him in his direction of travel while the "average car" merely attempts to maintain the mean speed of the traffic stream. Both

methods have been found to perform poorly in low density traffic and the floating car technique is impractical in congested flow (81).

A modification of the average car method was developed by Wardrop and Charlesworth (83), but it has since been tested in the field with only slight success (7, 63). A moving test vehicle was also used by Forbes (20) to measure judgment and perception time in the passing maneuver.

Moving vehicle procedures find application in quick, inexpensive surveys of limited scope where accuracies of better than $\pm$ 10% are not required.

Automatic Ground Devices

Most frequently employed today are a multitude of mechanical, electrical and electronic devices for collecting and recording various traffic information. Often used in collaboration with manual or moving vehicle techniques as well as by themselves, the automatic systems currently represent the most efficient and rapid means for obtaining large quantities of basic traffic data.

Among the forms automatic detecting devices take are pneumatic tubes, metallic tapes, radar, photoelectric cells, and magnetic or electronic sensors (4, 47, 59). Recording is generally done either graphically with pens scribing on a moving strip-chart or with a digital recorder (59). Nearly all applications of automatic methods are of a "time-spot"

nature. These include volume counts, spot speed surveys, and lateral placement detection. "Time-space" studies of required passing distances (46) and intersection delays (49) have been attempted by spacing detectors at intervals throughout an entire section of highway or intersection.

Expensive equipment, vandalism, railway tracks, roadway ice and snow, and freezing clock mechanisms are common problems associated with automatic systems (4, 8, 12).

Photography

Photography has often been suggested as a valuable tool in the collection of traffic data, particularly when a "time-space" technique is required. As early as 1927, the speed, volume and headway elements of vehicle flow were being studied with the aid of aerial photographs (50). By 1933, Greenshields (34) had developed a terrestrial, time-lapse motion picture technique which yielded accurate speeds and headways. Greenshields, Shapiro and Erickson (41) reported in 1947 on a time-lapse movie procedure for studying an urban street intersection from an elevated observation post. In the same year, Greenshields (37) noted the potential uses of aerial photography in traffic studies. The aerial reconnaissance requirements of World War II encouraged the perfection of continuous strip photography (86). In recent years, Chicago Aerial Survey, a division of Chicago Aerial Industries, has pioneered the application of stereo continuous strip photography to the study of traffic flow (84, 73).

Oblique 16 mm movies from a ground or tower observation point have been successfully employed for short duration studies of vehicle lateral placement (31), traffic behavior on freeway acceleration and deceleration lanes (52, 67), and travel time (81). Analysis of the filmed data is usually performed by projecting the movies, frame by frame, on a screen, and measurements are taken using a perspective grid system superimposed on the image.

To conserve film when conducting studies over an extended duration, time-lapse movie and intermittent photo techniques have been developed for terrestrial use (9, 16, 34, 37, 78, 23). Speed, volume, headway, type classification, weaving and lateral placement data for expressway traffic have been recorded in this manner by Covault (14) and Forbes (21), while driver behavior at intersections has been photographed by Cysewski (15), Davidson (16) and Greenshields (36). May (58) used time-lapse photography in making an inventory of environmental conditions along his study routes. Reduction of the data is normally accomplished by projecting transparencies onto a screen and scaling distances with a perspective grid system. To facilitate the identification of vehicles on the individual frames, Covault employed color photography.

Terrestrial time-lapse movies and intermittent photography are, at best, "time-limited space" in function. For surveying traffic characteristics over a length of highway or at a large intersection, aerial photographic methods, which

are truly "time-space" in scope, have proved useful. In 1927, Johnson (50) used standard stereo aerial photography to determine speeds, volume and headways on a major highway in Maryland. At an enlarged scale of 1" = 115', Johnson experienced little difficulty in identifying individual vehicles or obtaining sufficiently precise measurements. Forbes (20), in 1939, utilized 16 mm time-lapse aerial movies for measuring the judgment and perception time involved in a driver's passing maneuver. Although the method permitted great mobility and yielded accurate results, the costs and time associated with the reduction of the data were prohibitive. Forbes and Reiss (24) employed 35 mm aerial photography taken at 3500 - 4000 feet in an investigation of driver behavior. Speed and volume surveys have been made from aerial photos by Terry (77), Greenshields (37) and Jordan (51). The application of photogrammetry in traffic density studies was the subject of a report by Wagner and May (80).

In 1947, Greenshields (38) suggested the use of a helicopter, blimp or small aircraft for photographing traffic patterns at intersections. Bennet and Owen (6) reported, in 1948, on a helicopter photography study of an intersection in Dayton, Ohio. Captive balloons have been employed in Great Britain for similar purposes (29), and recently Dubuisson and Burger (17) used aerial photographic procedures to survey complex urban intersections in France.

The last decade has seen an increased use of continuous strip photography in transportation engineering (85, 86). Highway applications have included a study of tunnel approach traffic by the Port Authority of New York in which speed, vehicle type, lane use and density quantities were gathered simultaneously (73). The Sonne continuous strip technique affords a significant improvement in data reduction efficiency over that associated with standard stereo aerial photographs (84).

Rapid and simultaneous collection of a wide variety of "time-space" traffic data, recorded in a permanent and readily interpreted form, recommend photography as a possible means of securing information on the character of traffic flow. However, the expense of obtaining and reducing this data has, to date, been considered prohibitive.

The Ideal Data Gathering Method

Specific criteria governing data collection methodology naturally depend on the exact nature of a particular traffic survey. However, certain basic requirements of an "ideal" technique may be generalized.

The ideal data gathering method would:

1. Study flow characteristics over "space" as well as time;
2. Collect basic flow data on speed, volume and density along with time and distance spacing of

vehicles, lateral placement, acceleration, lane use, travel time, and vehicle classification information;

3. Measure intangible or psychological stimuli and response as well as physical factors;
4. "View" the entire section of highway under study;
5. Adapt readily to any roadway geometry or site and traffic condition;
6. Be operable in all common weather conditions;
7. Yield data which can be analyzed by statistical methods;
8. Adapt to sampling techniques;
9. Strike an equitable balance between economy and accuracy;
10. Be capable of a measurement accuracy to within ± 5 percent of the true value (47);
11. Collect data in the field;
12. Investigate normal traffic without letting the method itself influence or bias the patterns of flow;
13. Collect data at all sites of interest during the same time period;
14. Collect simultaneously all pertinent data for a given site;
15. Observe and record all elements of the traffic stream continuously;

16. Permit analysis on the basis of individual drivers and flow characteristics as well as average driver behavior and general flow patterns;

17. Permit classification of the vehicles by direction and lane;

18. Facilitate a rapid and accurate analysis of the raw data; and

19. Produce a permanent, compact record of the data.

No single method yet conceived can successfully fulfill all of these conditions. It is, therefore, the task of the traffic engineer to invoke his judgment and experience when selecting the technique which comes closest to meeting the needs of a particular study.

PURPOSE AND SCOPE

It was the purpose of this research to study, in terms of applicability, accuracy and efficiency, three methods of collecting traffic flow data. An automatic mechanical traffic survey device and the time-lapse aerial photographic technique were investigated in detail relative to their ability to detect and record volume, speed, vehicle spacing and lane use information. Consideration was also given to their use in gathering density, acceleration, vehicle placement, minimum passing distance, and other pertinent flow data. The third alternative, stereo continuous strip aerial photography, was similarly studied using the reported results of experiments by other researchers (84).

A detailed analysis of each method was made with reference to its:

a. Applicability to the gathering of traffic flow data;

b. Precision and accuracy; and

c. Costs and time involved in detecting, recording, and reducing the data.

A second consideration was the development of relationships between the volume, speed, density and vehicle spacing data obtained on multilane highways in the course of this research and to compare these findings with those of previous investigators.

DESCRIPTION OF THE STUDY METHODS

The Standard Vertical Aerial Photographic Technique

Concept

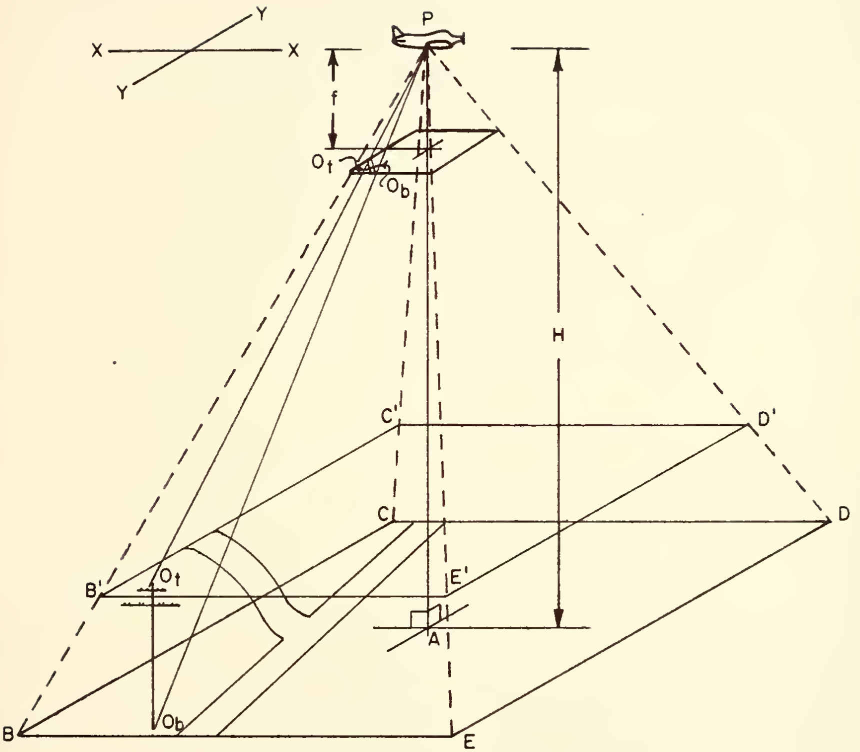
The vertical view of all points on a horizontal plane surface yields an image of unchanging scale provided a single height of observation above the surface is maintained. The aerial photography technique permits a recording, with certain inherent distortions, of this image on a photographic film. Since each exposure is but a point observation of a finite area, only one point on the horizontal plane is actually viewed vertically from above. This is illustrated diagrammatically in Figure 1. As shown, only point A, the center (principal point) of the field of view enclosed by BCDE, is viewed vertically. The scale factor for the photograph is defined at point A by the relationship:

$$s = \frac{H}{f}$$

where s is the scale factor

f is the focal length of the lens in inches

and H equals the elevation above ground of the lens (aircraft) in feet.



A = principal point
BCDE = field of view

FIGURE 1. GEOMETRY OF VERTICAL AIRPHOTO TECHNIQUE

The camera's precision lens permits distances on a given horizontal plane to be recorded with virtually no scale distortion. Objects in relief will appear on any other horizontal plane at a greater or lesser scale and displaced in the perspective view radially from the principal point (Figure 1).

Tilting of the aircraft about either the xx axis (roll) or yy axis (pitch), thereby causing the lines of sight to elongate or shorten, represents another source of image distortion. The necessity of rectifying these errors depends upon their magnitude and the level of accuracy desired.

Through a partial overlapping in the fields of view of two vertical photos taken at slightly different, but known, points in time and space, the motion of ground objects, such as motor vehicles, can be measured and recorded in terms of distance per unit time. In addition, measurements of headways between moving objects and their positions relative to fixed points can be obtained directly from the aerial photographs provided the scale factor is known.

Procedure - Data Gathering

The Indiana State Highway Commission, Bureau of Photogrammetric and Electronic Processes, secured and processed the intermittent aerial photography used in this research.

Employing a K-17C aerial camera* (see Figure 2) adapted for a high speed recycling of two seconds or better and mounted in a State owned Piper Apache aircraft, nine inch by nine inch photography was obtained at five level and tangent highway locations in Hammond and Indianapolis, Indiana. By virtue of a 12-inch nominal focal length lens and an 1800 foot flight elevation, a photo scale of approximately 150 feet per inch was maintained.

As estimated by the following relationship,** a 72 percent overlap was sufficient to assure the appearance of nearly all vehicles in at least two photographs when a three second time interval between exposures was employed:

$$Q = \frac{\frac{1}{2} \quad Is + S_v' \ (t)}{Is} \ (100)$$

where

Q = percent overlap

I = the photographs' dimension, in inches, parallel to the line of flight

s = scale of photography in feet per inch

S_v' = maximum expected vehicle speed in feet per second

t = time interval between exposures in seconds

Setting $I = 9$ inches, $s = 150$ feet/inch, $S_v' = 100$ feet/second, and $t = 3$ seconds, a Q of 72 percent results.

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* See Appendix A, Specifications of the K-17C Aerial Camera.

** See Appendix B for the derivation of the overlap equation.

FIGURE 2. PIPER APACHE AIRCRAFT AND K-17C AERIAL CAMERA

This interval-overlap combination was achieved by maintaining an aircraft ground speed (S_p) of approximately 126 feet per second (85 miles per hour) as determined from the relationship:

$$S_p = \frac{Is\ (1 - Q)}{t}$$

Ground control for scaling purposes was established by field measurements, to the nearest 0.5 foot, of expansion joint spacing along the concrete pavement.

From four to eight tangent flight runs were made at each site during evening periods of high traffic volume in the Summer and Fall of 1962. Each photo pass extended from one to two miles in length. By flying in a direction opposite to the major flow, the amount of data obtained per run was maximized. Table 1 summarizes the various flight plans utilized in this study. Four of the sites were photographed with Eastman Super XX or Plus X, Aerographic black and white film. A fifth location was photographed with Eastman Aero-Ektachrome color film. The date, time of day, duration of run, shutter speed and lens aperture were recorded for each flight pass. A two man crew of a pilot and photographer proved adequate for obtaining the desired data.

Processing of the black and white photography was done in a Morse rewind type B-5 unit. One set of double weight contact prints was made for use in data reduction and analysis. A second set of identical prints on lightweight stock was used

TABLE 1. SUMMARY OF AERIAL PHOTOGRAPHY FLIGHT PLANS

			Photo Coverage		Distance			Flight Plan	
No.	Location	Route	From	To	(Miles)	Date	Passes	Time	Direc.
1	Hammond	Tri-State	Calumet Ave.	Ind'pls Blvd.	1.5	6/14/62	3	4:45-5:00PM	W
2	Hammond	Tri-State	Calumet Ave.	Ind'pls Blvd.	1.5	6/14/62	3	6:00-6:10PM	W
3	Hammond	Toll Road	Cline Ave.	Kennedy Ave.	1.5	6/14/62	4	5:10-5:30PM	W
4	Indianapolis	S.R. 100	10th St.	21st St.	1.0	8/10/62	2	4:45-4:50PM	N
5	Indianapolis	S.R. 100	10th St.	21st St.	1.0	8/10/62	2	5:20-5:30PM	N
6	Indianapolis	Arlington Ave.	38th St.	46th St.	1.0	8/10/62	3	5:00-5:15PM	N
7	Indianapolis	U.S. 31	Pleasant Run	P.R.R.	0.9	9/10/62	5	4:50-5:15PM	N
8	Indianapolis	U.S. 31	Pleasant Run	P.R.R.	0.9	9/10/62	3	5:30-5:45PM	N
9	Hammond	Tri-State	Calumet Ave.	Ind'pls Blvd.	1.5	10/18/62	8	5:00-5:45PM	W

No.	Altitude Above Ground	Scale	Percent Overlap	Photo Interval	Approx. No. of Photos per Run	Film	Camera	Aircraft	Est. Flight Time From Indianapolis
1	1800'	1"=150'	65-75%	3 sec.	20	B & W	K-17C	Apache	4.5 hours
2	1800'	1"=150'	65-75%	3 sec.	20	B & W	K-17C	Apache	
3	1800'	1"=150'	65-75%	3 sec.	20	B & W	K-17C	Apache	
4	1800'	1"=150'	65-75%	3 sec.	12	B & W	K-17C	Apache	1.5 hours
5	1800'	1"=150'	65-75%	3 sec.	12	B & W	K-17C	Apache	
6	1800'	1"=150'	65-75%	3 sec.	12	Color	K-17C	Apache	
7	1800'	1"=150'	65-75%	3 sec.	10	B & W	K-17C	Apache	1.5 hours
8	1800'	1"=150'	65-75%	3 sec.	10	B & W	K-17C	Apache	
9	1800'	1"=150'	50%	4 sec.	15	B & W	K-17C	Apache	4.0 hours

for constructing a photo index of each study site. Figure 3 illustrates, at a reduced scale, the nine inch by nine inch photographs. The color photography was also processed in the Morse B-5 tanks and developed as a roll of nine inch by nine inch positive transparencies.

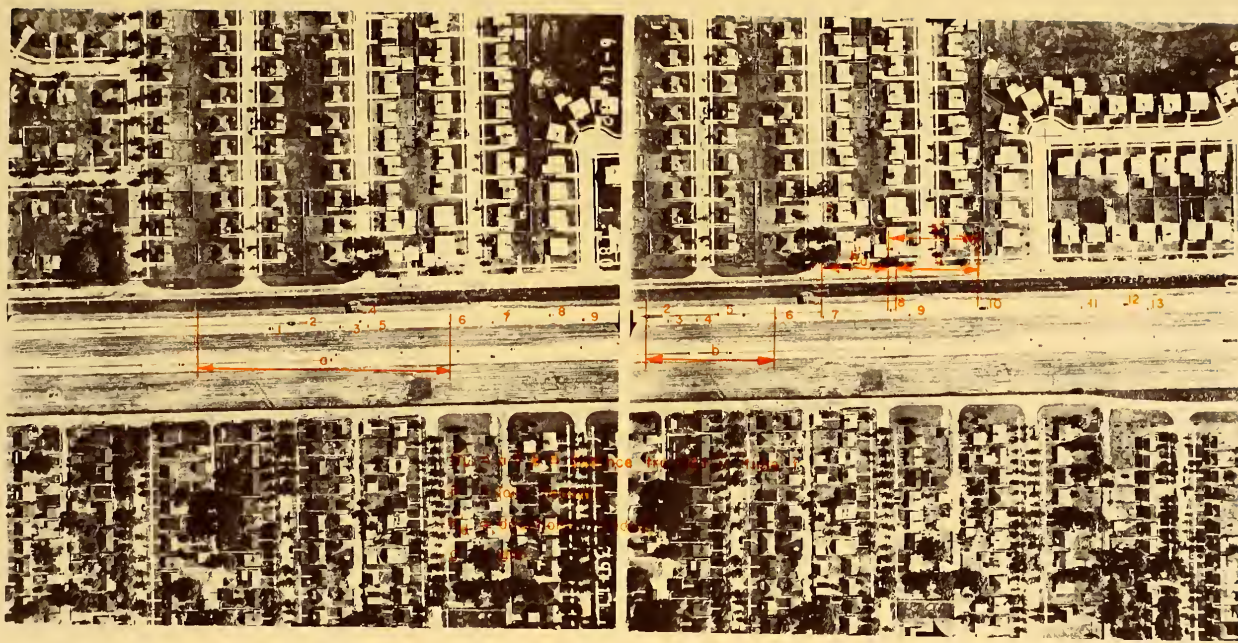
Procedure - Data Reduction

Speed and distance headway quantities were obtained from the aerial photographs by simple linear measurements employing a 100 unit per inch engineers' scale, lead or grease pencils and prepared data sheets. A hand or stand mounted magnifying glass was also used by some of the data processors to facilitate the precise measurements required.

Four students enrolled at Purdue University were hired to reduce the data. Each was instructed to adhere to the following general procedure:

The black and white photographs were separated into sets representing individual flight passes over a specific highway location. Each exposure having been numbered at the time of processing, the segregation of prints was rapidly and accurately accomplished.

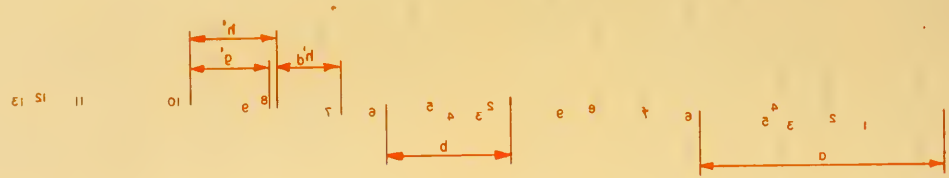
Each photo set was reduced independently. First, the scale of photography was determined from the ground control afforded by the pavement expansion joints. Any significant change in scale over the length of flight was noted. Barring major variations, the mean scale value for all photos of a given site and day was used in the data analysis.



9 inch x 9 inch Exposures Reduced To Half Size

FIGURE 3a.

FIGURE 3. STANDARD VERTICAL AERIAL PHOTOGRAPHY AND EXAMPLES OF TRAFFIC DATA OBTAINED



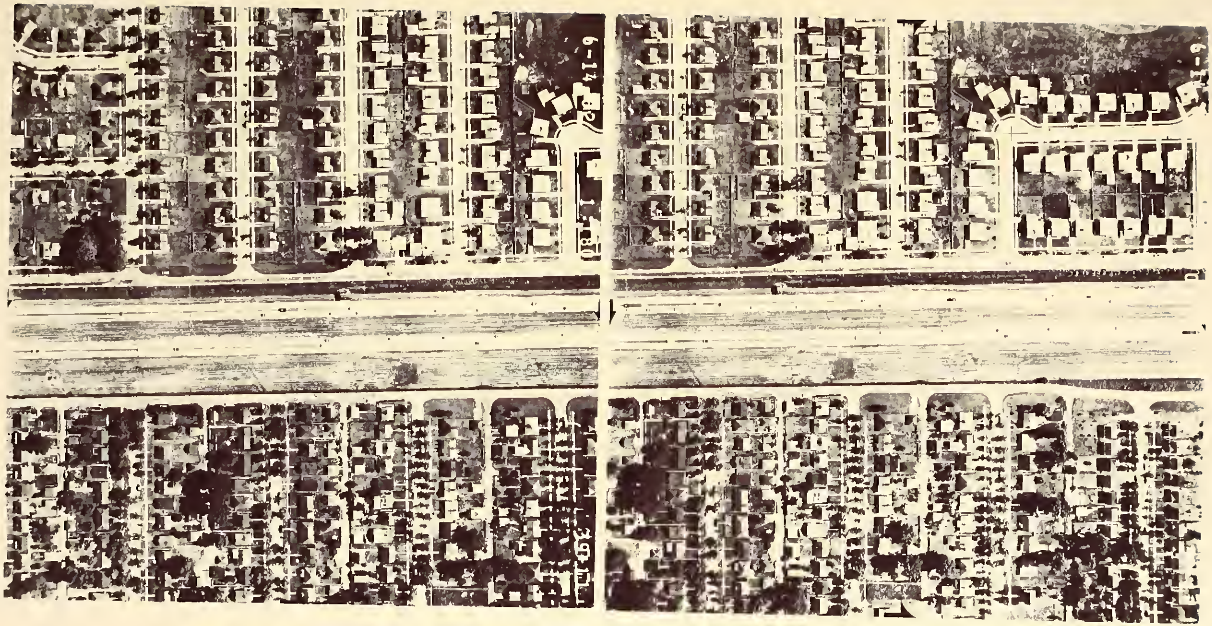
$D'_v = a + b =$ distance traveled in time t

$h' =$ lane headway

$h'_d =$ directional headway

$g' =$ gap

FIGURE 3a.



9 inch x 9 inch Exposures Reduced To Half Size

FIGURE 3. STANDARD VERTICAL AERIAL PHOTOGRAPHY AND EXAMPLES OF TRAFFIC DATA OBTAINED

Viewing the photo pairs with a simple lens stereoscope permitted an approximately level section of tangent highway to be accurately defined for each site. The time interval between successive exposures was established for each flight run by the relationship:

$$t = \frac{t_p}{n - 1}$$

where

t is the photo interval in seconds

t_p is the time duration of the flight run in seconds

and

n represents the number of photos comprising the run.

Since t_p had been recorded only to the nearest second, a more accurate determination of the exposure interval was desired. An acceptable value was found in the mean of the calculated t's for all the runs made on a given day and at a particular site. The assumption that the photographs for a given intervalometer setting were equally spaced in time was verified by tests conducted on the aircraft-camera-intervalometer system under simulated flight conditions*. Variations about the mean interval were found to be less than $\pm$ 0.05 seconds.

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* An Esterline Angus Model A.W. pen recorder, inserted into the camera-intervalometer circuit, was used to record graphically the time interval between shutter triggering electric impulses. These tests were conducted while the aircraft's engine was operating at approximately 2300 rpms.

The vehicles of interest - those flowing freely on the through travel lanes - were identified on the photographs and numbered successively, by direction of flow, from the start of the photo run (see Figure 3a). Numbering was done directly on the prints with a lead or grease pencil.

Each vehicle appeared in at least two photographs. This permitted its speed to be obtained by measuring its progress along the roadway during the time interval between photos. In the interest of consistency, the first two successive exposures in which a given vehicle appeared were used when making this measurement. A location on the highway common to both photographs served as a reference point to which the measurements could be scaled from the front bumper of the vehicle in question (see Figure 3a). These distances on the photographs were estimated with a 100 units per inch engineers' scale to the nearest 0.005 inch. At a 1:1800 scale of photography, this represented a ground distance precision of $\pm$ 4.5 inches. The procedure yielded two values which were then added algebraically so as to give the photographic distance traveled (D'_v)*. (Note: throughout the text a prime (') is used to denote measurements on the photographs.) The result was recorded on prepared data sheets along with a classification of each vehicle by type, lane and position on the photos (see Figure 4). The photographic distance traveled

---

* D'_v may also be obtained directly on a stereo view of the route. See Appendix D.

Speed Data Sheet
Form A

Site - 31
Direction of Traffic - S.
Flight No. - 46-1 to 46-8
Flight Direction - N.
Date of Flight - 9/10/62
Reduced by - GFK

Vehicle Types

P = pass. car or light truck
M = medium truck
T = heavy truck
B = bus

Interval - 3 sec.
Scale - 1:1800

Lanes

W or N

1 2 3 4 5 6

E or S

Lead Photo	Following Photo	Veh. No. From Start of Flight	Lane	Veh. Type	Veh. No. On Lead Photo	Travel Distance (D'_v) (1/100")
72	73	1	1	M	1	81.5
72	73	2	1	M	2	82.0
73	74	3	3	P	3	164.5
73	74	4	2	P	4	117.5
73	74	5	3	P	5	163.0
74	75	6	1	P	4	137.5
75	76	7	3	P	2	163.0

FIGURE 4. VEHICLE SPEED AND CLASSIFICATION DATA SHEET FOR TIME-LAPSE AERIAL PHOTOGRAPHY

(D'_v) can be converted to ground distance traveled (D_v) by use of the appropriate scale factor (s).

Although vehicle speed was recorded in terms of distance traveled in time interval t, conversion into miles per hour was accomplished using the equation:

$$S_v = \frac{.682\ D_v}{t}$$

where

S_v = vehicle speed in miles per hour

D_v = $D'_v(s)$ = ground distance traveled by the vehicle in time t

D'_v = vehicle travel distance in time t as measured on the photos in inches

s = scale of photography in feet per inch

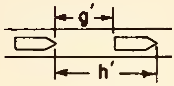
and

t = time interval, in seconds, between successive exposures

"Headway" is commonly defined in traffic engineering as being the elapsed time between the passing of a fixed point on the highway of a common point (e.g. the front bumper) on two successive vehicles. The time-lapse aerial photography technique, being essentially a moving point that is recording vehicle positions as it surveys the route, cannot yield this quantity directly. Therefore, "by lane" headways were initially determined from distance measurements, as designated by "h′" in Figure 3a and also in Figure 5.

Headway Data Sheet
(by lane)

Form B



Site - 31
Direction of Traffic - S.
Lane - 1
Flight No. - 46-1 to 46-8
Flight Direction - N.

Vehicle Types

P = pass. car or light truck
M = medium truck
T = heavy truck
B = bus

Date of Flight - 9/10/62
Interval - 3 sec.
Scale - 1:1800
Reduced by - GLK

Lanes

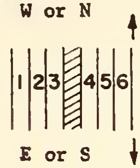


Photo No.	Lead Veh. From Start of Flight	Type	Following Veh. From Start of Flight	Type	Distance Headway, h' (1/100")	Distance Gap, g' (1/100")	Time Headway, h_t (sec.)
2	1	P	2	P	24.5	15.5	2.1
2	2	P	3	P	26.5	15.5	3.1
2	3	P	4	P	19.0	8.5	2.2
2	4	P	7	P	131.0	121.5	4.8
3	7	P	15	P	484.0	473.5	14.4
4	15	P	21	P	240.0	228.5	6.8
4	21	P	26	P	109.0	98.5	3.2

FIGURE 5. HEADWAY AND GAP DATA SHEET FOR TIME-LAPSE AERIAL PHOTOGRAPHY

$$h = h'(s)$$

where

h = distance headway in feet

h' = distance headway as measured on photos in inches

s = scale of photography in feet per inch

A division of the distance headway by the speed of the "following" vehicle in feet per second (S_f) yielded a time headway (h_t) in seconds:

$$h_t = \frac{h}{S_f}$$

Headways were found to within $\pm$ 5 inches of ground distance or, at S_f = 50 mph, $\pm$ .01 seconds.

Occasionally the "following" vehicle of a headway pair failed to appear in the same photograph as the "lead" vehicle. Appendix C describes the "bridging" method employed for estimating headways for such cases.

Concurrent with the headway measurement was a determination of the spacing or distance gap (g') between the rear bumper of the "lead" vehicle and the front bumper of the vehicle following in the same lane. This quantity, was obtained in essentially the same manner as the "by lane" distance headway.

Distance and time headways were also found on a "directional" basis using the general procedure outlined above (see Figure 3a). In this case, however, the "following" vehicle was not necessarily in the same lane as the vehicle ahead.

For two-lane study sections with two-way traffic, lane and directional headways were, of course, synonymous.

Traffic density (P) was established by simply counting the number of vehicles depicted in a photograph on either a "by lane" or "directional" basis. At a photo scale of 150 feet per inch, these single exposure densities could be expressed as vehicles per quarter mile.

Since each exposure was made at a slightly different period in time, traffic volumes could not be determined directly from a count of the vehicles pictured. Two techniques were developed for calculating an estimated route volume.

The "Speed-Density" technique employs the relationship

$$V = P\,\bar{S}_{v_1} \quad \text{.. Eq. 1}$$

where

V = traffic volume in vehicles per hour

P = density in vehicles per mile

$\bar{S}_{v_1}$ = space mean vehicle speed in miles per hour*

---

* The space mean speed is defined by

$$\bar{S}_{v_1} = \frac{dn}{\sum_{i=1}^{n} t_i}$$

where

Vehicle speed and instantaneous density data were reduced directly from the individual photographs and a volume (V_i) calculated for each exposure. The volume for an entire flight run (V) was the mean of the $V_{i's}$ for that particular series of photos. For traffic moving opposite to the direction of flight this method tended to be biased by the slower moving vehicles which often appeared in more than two pictures, thereby yielding a volume lower than the true value. The converse held for the case in which the aircraft was moving directionally with the vehicles.

---

d = travel distance

t_i = time for vehicle i to travel distance d

and

n = number of vehicles observed.

The reduction procedure employed in this research yielded a time mean vehicle speed as given by

$$\bar{s}_v = \frac{\sum_{i=1}^{n} (d_i/t_i)}{n}$$

Whenever there is a variation among vehicle speeds, $\bar{s}_v > \bar{s}_{v_1}$. If, however, all vehicles are traveling at the same velocity, $\bar{s}_{v_1} = \bar{s}_v$. Such homogeniety of velocity is assumed for the Speed-Density and Speed Ratio volume estimates (see reference 81).

The "Speed Ratio" technique for estimating route volumes is based on a relationship between vehicle and aircraft velocities. As in the previous discussion, volume is considered as a function of average vehicle speed and route density.

First, a volume study section was defined by establishing the terminals A and B at locations which appeared as principal points on photographs exposed at or near either end of the photo run (see Figure 6). The number of vehicles (n_{t_p}) appearing between these two points was recorded. The duration of the flight pass (t_p), as determined in the field, served as a time base for the vehicle count.

For the aircraft traveling in a direction opposite that of the traffic stream in question, the following discussion governs the development of the appropriate volume equation:

Utilizing manual or automatic ground techniques, route volumes were secured by recording the number of vehicles passing a fixed location during a specified period of time, When determining traffic volumes from aerial photography, however, one must be cognizant of the fact that both the reference point (or aircraft) and the vehicles were in motion. Since the airborne camera did not photograph an entire section of highway, A-B, at the same instant in time, the total number of distinct vehicles appearing in a series of exposures represented not only those vehicles in the study section at the flight start, but also those which passed point B over

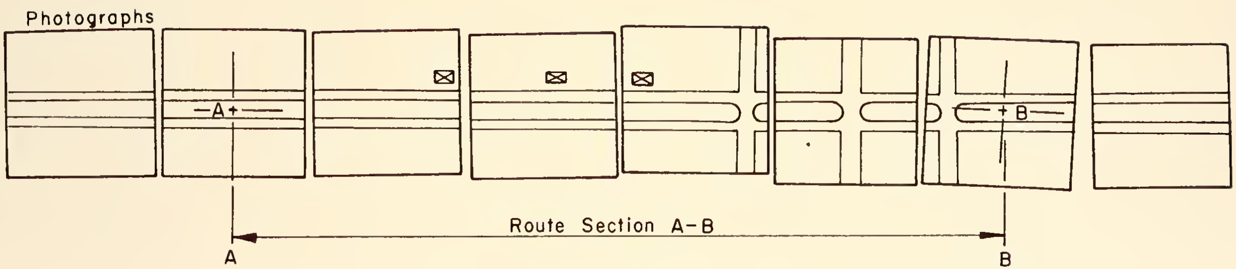


FIGURE 6. ROUTE SECTION A–B FOR VOLUME CALCULATION BY "SPEED RATIO" METHOD

the duration of the flight run (see Figure 7). It was this volume at B during a time t_p which the Speed Ratio method approximated.

Two assumptions were inherent in the development of equations 2 thru 6. All vehicles were considered to be traveling at: (1) the calculated average speed ($\bar{s}_v$); (2) equal headways. The flight duration time (t_p) was equated by

$$t_p = (N - 1)\, t$$

where

N = the number of exposures between and including the terminal photos in which A and B are principal points.

and

t = the time interval between exposures in seconds.

With the plane flying counter to the traffic, the stream volume for time t_p was

$$V_{t_p} = \frac{BC}{AC}\,(n_{t_p}) \quad \text{.................................Eq. 2}$$

where

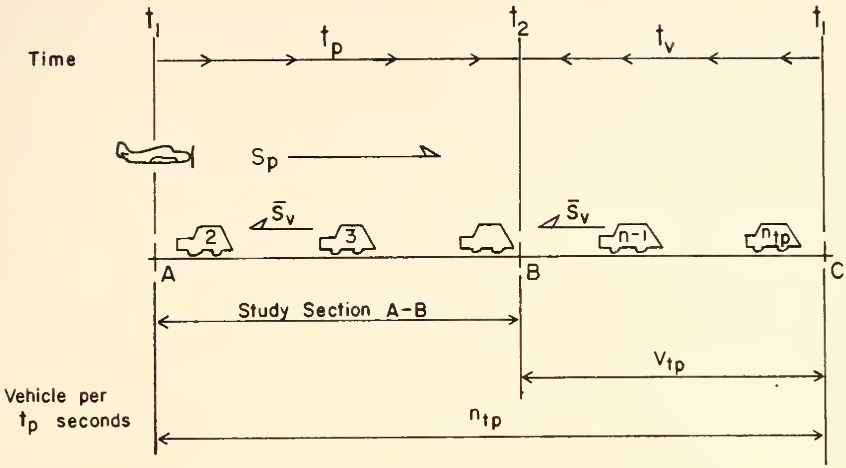
$$BC = t_v\,(\bar{s}_v)$$

$$AC = t_p\,(s_p) + t_v\,(\bar{s}_v)$$

and

n_{tp} = number of vehicles per t_p seconds appearing between principal points A and B.

Therefore,



A = starting point of flight (photo principal point)

B = end point of flight (photo principal point)

BC = distance vehicles travel in time t_p

n_{t_p} = total number of distinct vehicles appearing on the airphotos between A and B (vehicles per t_p seconds)

S_p = speed of plane in feet per second

$\bar{S}_v$ = average vehicle speed in feet per second

$t_p = (t_2 - t_1)$ = time duration for flight from A to B in seconds

$t_v = (t_2 - t_1)$ = time, in seconds, required for vehicle n at point C to reach point B when traveling at $\bar{S}_v$. Defined as being equal to t_p.

V_{t_p} = vehicles passing point B in time t_p

FIGURE 7. "SPEED RATIO" CONCEPT FOR TRAFFIC VOLUMES FROM STANDARD AIRPHOTOS

VEHICLES AND PLANE MOVING IN OPPOSITE DIRECTIONS

$$V_{t_p} = \frac{t_v \ (\bar{s}_v)}{t_p \ (s_p) + (\bar{s}_v) \ t_v} \ (n_{t_p}) \ \text{.................Eq. 3}$$

Since t_v is defined in Figure 7 as being equal to t_p, then

$$V_{t_p} = \frac{\bar{s}_v}{s_p + \bar{s}_v} \ (n_{t_p}) \ \text{.........................Eq. 4}$$

Converting to vehicles per minute,

$$V_m = \frac{60 \ V_{t_p}}{t_p}$$

or, in terms of an hourly volume,

$$V = \frac{3600 \ V_{t_p}}{t_p}$$

When the aircraft was moving directionally with the traffic as shown in Figure 8 but at a speed greater than $\bar{s}_v$, the volume of traffic passing location B in time t_p was found from the relationship:

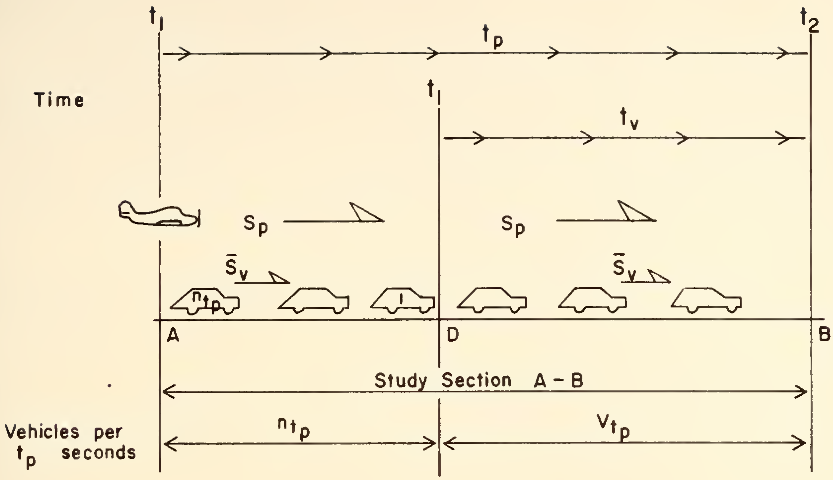
$$\frac{n_{t_p}}{AD} = \frac{V_{t_p}}{DB}$$

or,

$$V_{t_p} = \frac{DB}{AD} \ (n_{t_p}) \ \text{.................................Eq. 5}$$

where

$$DB = t_v \ (\bar{s}_v)$$



A = startinig point of flight (photo principal point)

B = end point of flight (photo principal point)

DB = distance vehicles travel in time t_p

n_{t_p} = total number of distinct vehicles appearing on the airphotos between A and B (vehicles per t_p seconds)

S_p = speed of plane in feet per second

$\bar{S}_v$ = average vehicle speed in feet per second

$t_p = (t_2 - t_1) =$ time duration for flight from A to B in seconds

$t_v = (t_2 - t_1) =$ time, in seconds, required for vehicle 1 to travel from point D to point B. Defined as being equal to t_p

V_{t_p} = vehicles passing point B in time t_p

FIGURE 8. "SPEED RATIO" CONCEPT FOR TRAFFIC VOLUMES FROM STANDARD AIRPHOTOS

VEHICLES AND PLANE MOVING IN THE SAME DIRECTION

and

$$AD = t_p\,(s_p) - t_v\,(\bar{s}_v)$$

With t_v being defined as equal to t_p, equation 5 becomes,

$$V_{t_p} = \frac{\bar{s}_v}{s_p - \bar{s}_v}\,(n_{t_p}) \quad \text{.........................Eq. 6}$$

It should be noted that equation 6 is meaningless when $s_p < \bar{s}_v$.

Although for the purposes of this research the study of data reduction efficiency was limited to the basic flow elements of volume, speed and spacing, information relative to lane usage, lane changing, vehicle acceleration and lateral placement was also obtained photogrammetrically.

Data reduction from the Ektachrome aerial photography was accomplished in essentially the same manner as described above. In this case, however, positive transparencies were viewed on a light table, all numbering and marking being done with a grease pencil directly on the "glossy" side of the photos.

The Sonne Continuous Strip Aerial Photography Technique

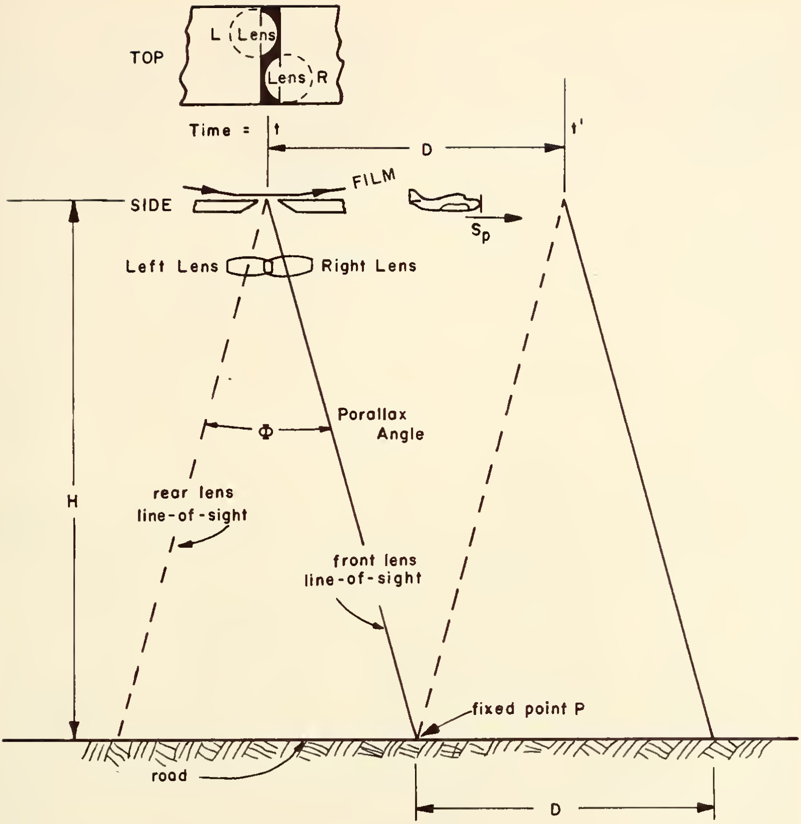
Concept

The principles underlying Sonne continuous strip stereo photography have been detailed in the literature (84, 86)

and, therefore, will only be highlighted here.

The continuous strip aerial technique attempts to compensate for relative image motion by moving the film past an aperture slit at a rate proportional to the height and ground speed of the aircraft. A Sonne camera and the geometry of the stereo photography are depicted in Figure 9. The camera system features a narrow, adjustable straight slit opening in the focal plane of two matched precision lenses which, together, expose the entire width of the film. The right hand lens is placed ahead of the slit and the left is situated aft, such that each commands a distinct rectangular field of view as defined by the aperture opening. Thus, each point on the ground is registered on half the film before the airplane passes overhead while the other half is exposed on the point after the aircraft's passing (see Figure 10). This, in effect, yields a stereogram which can be viewed in three dimensions with a Sonne viewer or projector.

For strip photography to yield an undistorted image, the film velocity must be synchronized with the image motion and the aircraft flown straight and level. Scale of photography is dependent upon the flight elevation above ground, lens focal length and film-image synchronization. The continuous strip principle permits large scale photography to be flown, with 100 feet per inch and 250 feet per inch scales predominating in highway location work (86).



t = time that front lens "sees" point P

t' = time that rear lens "sees" point P

D = distance flown between t and t'

H = flight height

S_p = plane speed

Reference: Wohl, M and Sickle, S.M., "Continuous Strip Photography—An Approach to Traffic Studies", Photogrammetric Engineering, Vol. xxv, No. 3, pp 397—403, June 1959.

FIGURE 9. DIAGRAM OF SONNE CAMERA AND PHOTO GEOMETRY FOR FIXED POINT

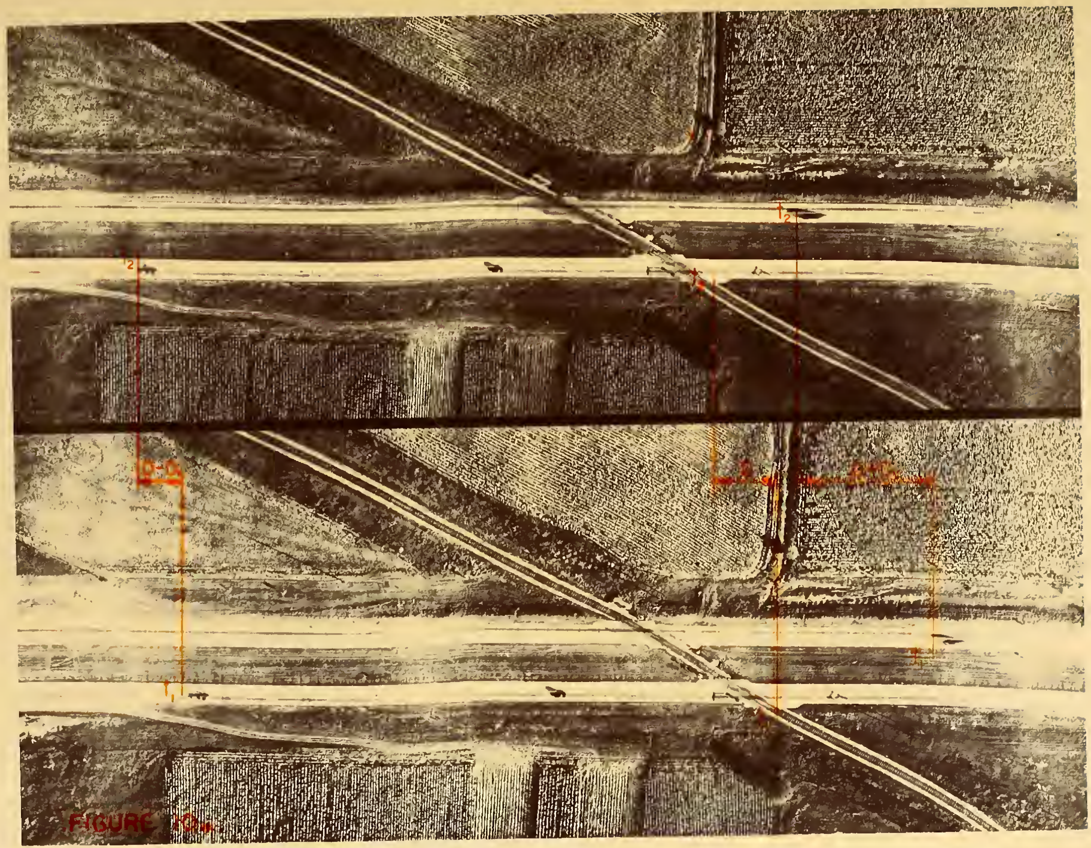


FIGURE 10. SECTION OF SONNE CONTINUOUS STRIP PHOTOGRAPH AND EXAMPLES OF TRAVEL DISTANCE (D_v) MEASUREMENT

FIGURE 10a.

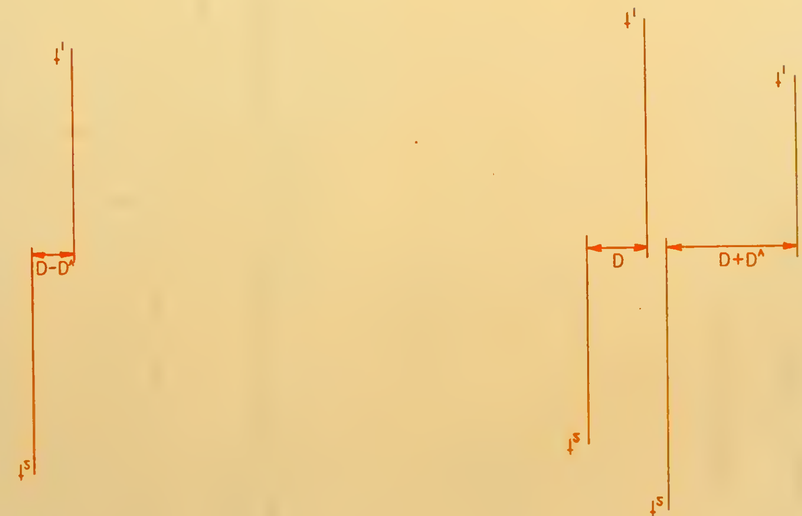


FIGURE 10. SECTION OF SONNE CONTINUOUS STRIP PHOTOGRAPH AND EXAMPLES OF TRAVEL DISTANCE (D_v) MEASUREMENT

Of particular interest in traffic studies is the time lag between the right and left hand exposures which permits vehicle speed to be calculated. The angle of parallax (Ø) between the front and rear lines of sight represents an airbase time lag which is constant for a given flight elevation (Figure 9). If the forward lens views a fixed point A at time t and the same point is recorded by the rear facing lens at t', the airbase, or distance D, is found by the relationship (84):

$$D = 2\ H \tan \text{Ø}/2$$

where

H is the flight elevation above ground

and

Ø is the parallax angle

At plane ground velocity S_p,

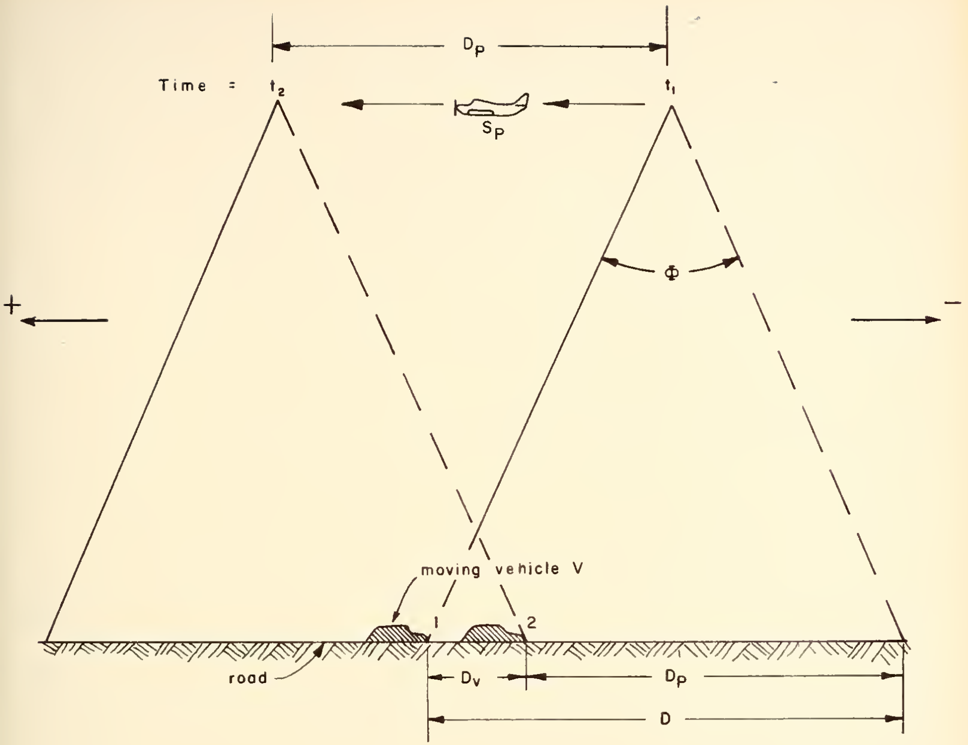
$$D = S_p\ (t' - t)$$

Thus, the airbase time lag (t' - t) is defined by

$$t' - t = \frac{2\ H\ \text{Tan}\ \text{Ø}/2}{S_p} \quad \text{.............................Eq. 7}$$

When concerned with a moving object on the ground, such as a motor vehicle, reference to Figure 11 yields equations 8 and 9 for the time lag $(t_2 - t_1)$:

$$t_2 - t_1 = \frac{D - D_v}{S_p} \quad \text{.............................Eq. 8}$$



S_P = plane speed

S_V = speed of moving vehicle

t_1 = time front lens sees vehicle at 1

t_2 = time rear lens sees vehicle at 2

D_P = distance flown between t_1 and t_2

D_V = distance vehicle moves between t_1 and t_2

Reference: Wohl, M. and Sickle, S. M., "Continuous Strip Photography — An Approach to Traffic Studies", Photogrammetric Engineering, Vol. xxv, No. 3, pp 397-403, June 1959.

FIGURE 11. DIAGRAM OF PHOTO GEOMETRY FOR MOVING VEHICLE

and

$$t_2 - t_1 = \frac{D_v}{S_v} \qquad \text{.................................Eq. 9}$$

where

D = airbase (feet)

D_v = distances vehicle V moves in time $t_1 - t_2$ (feet)

S_p = plane ground speed (feet per second)

S_v = speed of vehicle (feet per second)

Equations 7, 8 and 9 serve to emphasize the importance of knowing the aircraft's elevation and ground speed in the continuous strip analysis.

Among the most common sources of error in linear measurements from aerial photographs are the image distortions attributable to roll and pitch of the aircraft. Gyrostabilization of the Sonne camera about the roll axis renders insignificant the amount of roll occurring between the two views of any given vehicle. Furthermore, with vehicle movement generally being parallel to the flight line, roll has little effect on the accuracy of speed, headway or volume measurements. Therefore, roll can be discounted as a significant error in traffic studies.

Tilt about the pitch axis is usually more pronounced than roll. However, an electronic control device within the camera system automatically causes the film velocity to change with variations in the degree of pitch. This adjusts the airbase so as to compensate for the scale distortion. In the event that a constant pitch position is maintained by the

plane, each half of the film will be of a different scale. However, none of the basic measures of traffic flow necessitates the use of the scales for both images. Furthermore, for the levels of precision demanded in traffic surveys, time consuming corrections for pitch would seem unnecessary.

Procedure - Data Gathering

There was no continuous strip photography flown specifically for this research. Therefore, the following discussion on procedure is necessarily presented in very general terms.

For the most part, the same considerations must be made when planning and conducting a continuous strip traffic survey as are associated with a time-lapse aerial photographic study. Synchronization of film speed and image motion is assured through the use of optical and electronic devices capable of sensing and correcting for variations in aircraft velocity and altitude.

It is particularly important that the aircraft's speed be accurately determined. At the low altitudes common in strip photography, this is most readily accomplished by an airborne observer who, by means of a view finder and stopwatch, can record the flight time between landmarks along the highway and then compute an average ground speed for the plane.

To minimize the image distortions associated with tilt, Sonne photo flights should be made at elevations of 1000 feet or less. Therefore, using lenses of 4-inch focal length, scales of 250 feet per inch or larger are obtained. To be free of scale distortions, strip photography must be flown on a straight line. Curvilinear highway sections are best surveyed by flying a series of tangents to the study site.

Procedure - Data Reduction

The procedures for reducing basic traffic data from strip photography have been discussed in the literature (84) and are summarized below.

Two methods have been suggested for determining vehicle speeds. The first relates vehicle velocity to the distances traveled by the aircraft (D_p) and the vehicle (D_v) in the time interval $t_2 - t_1$ (see Figure 11). The speed equation is developed from the following relationships (84):

$$S_v = \frac{-D_v}{t_2 - t_1} \qquad \text{.......Eq. 10}$$

where

S_v = vehicle speed in feet per second

Since $D_p = S_p\ (t_2 - t_1)$,

$$t_2 - t_1 = \frac{D_p}{S_p} \qquad \text{.......Eq. 11}$$

where

S_p = speed of the plane in feet per second

From Figure 11, $D_p = D + (-D_v)$ ....Eq. 12

where

D = airbase or photo offset in feet

Substituting equations 11 and 12 into 10,

$$S_v = S_p \frac{-D_v}{D + (-D_v)} = - S_p \frac{D_v}{D - D_v} \; ^{*} \qquad \text{..........Eq. 13}$$

When the vehicle and plane are moving in the same direction, equation 13 becomes

$$S_v = S_p \frac{D_v}{D + D_v} \qquad \text{..........................Eq. 14}$$

Measurements of D and $(D \pm D_v)$ may be secured directly from the strip photo and D_v calculated. Having obtained the aircraft's speed in the field, either equation 13 or 14 may be used to establish vehicle speeds.

An alternate technique** employs a Sonne stereo viewer-comparator system by which the difference in parallax ($\triangle$ p) between the moving vehicle and the roadway is determined by bringing first the highway and then the auto into stereo. The associated speed equation is:

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* When the aircraft is flying opposite the direction of traffic.

** Developed by D. R. Shurz, Instructor of Photogrammetry, Massachusetts Institute of Technology.

$$S_v = S_p \frac{\Delta p}{\Delta p + D} \quad \text{.........................Eq. 15}$$

Although both techniques yield accurate results, the latter is regarded as being the more efficient and would probably lend itself more readily to an automatic readout system.

Since each image along a continuous strip photograph is recorded at a different point in time, a direct measurement of distance headway is impossible. Reference to Figure 12 shows that the headway (h) between vehicles L and F may be equated as follows:

$$h = D_p + D_F \quad \text{.........................Eq. 16}$$

where

$$D_F = S_F \, (t_F - t_L) \quad \text{.........................Eq. 17}$$

and

$$D_p = S_p \, (t_F - t_L) \quad \text{.........................Eq. 18}$$

or

$$t_F - t_L = \frac{D_p}{S_p} \quad \text{.........................Eq. 19}$$

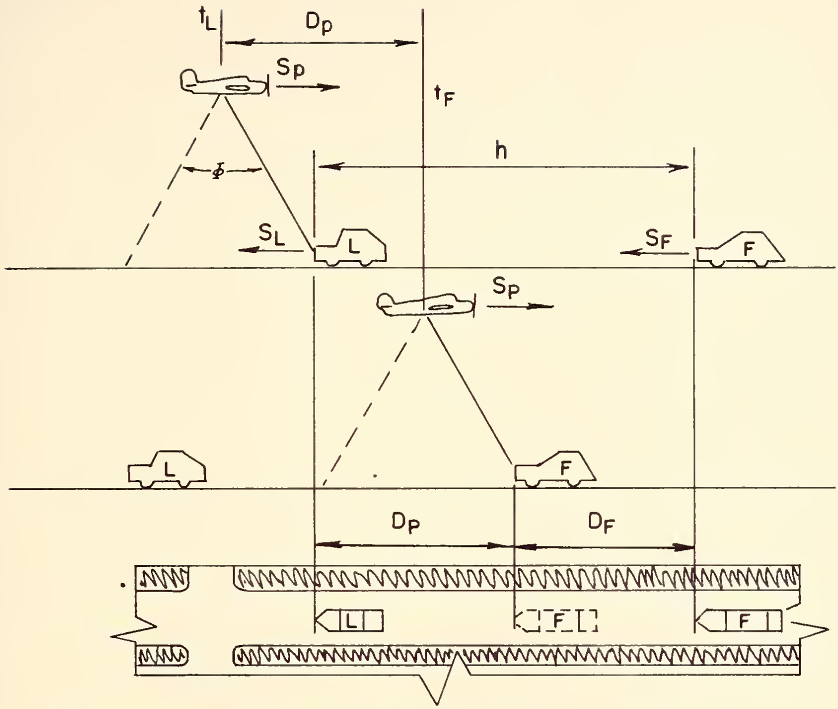
where

t_L = time the lead vehicle is recorded

t_F = time the following vehicle is recorded

D_F = distance in feet, that vehicle F moves in the interval $(t_F - t_L)$

D_p = distance in feet, the plane travels between t_L and t_F



h = distance headway between vehicles L and F

t_L = time the lead vehicle (L) is recorded

t_F = time the following vehicle (F) is recorded

D_F = distance the following vehicle moves in the interval $(t_F - t_L)$

D_P = distance the plane travels in the interval $(t_F - t_L)$

S_F = speed of the following vehicle

S_L = speed of the lead vehicle

S_P = plane speed

FIGURE 12. HEADWAY DETERMINATION FROM CONTINUOUS STRIP PHOTOGRAPHY

and

S_F = velocity of the following vehicle in feet per second

Substituting equation 19 into 17

$$D_F = \frac{S_F\ (D_p)}{S_p} \quad \text{.............................Eq. 20}$$

Equation 16 becomes

$$h = D_p + \frac{S_F\ (D_p)}{S_p} \quad \text{.............................Eq. 21}$$

where S_p is known, D_p can be measured and S_F is calculated from equation 15.

In the case where the flight direction is the same as the vehicles, equation 21 becomes

$$h = D_p - D_F = D_p - \frac{S_F\ (D_p)}{S_p} \quad \text{.....................Eq. 22}$$

Relationships for directional volume similar to equations 4 and 6 for the intermittent photography were developed (see Figure 13) by taking into account the aircraft's velocity relative to that of the vehicles and the "changing time" nature of the photography. When the vehicles and plane are moving in opposite directions, the volume expression is

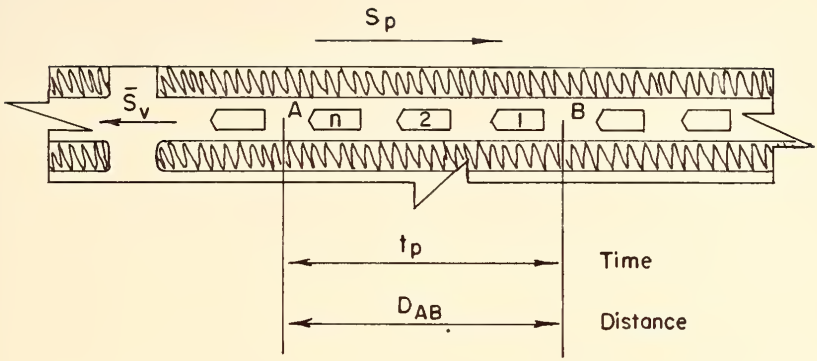
$$V = \frac{S_p}{D_{AB}} \left[\frac{\bar{S}_v}{S_p + S_v} \right] n \quad \text{........................Eq. 23}$$

where

$\bar{S}_v$ = average speed of n vehicles

D_{AB} = length of highway section AB

n = number of vehicles photographed in section AB



V_{t_p} = vehicles passing point B during the flight run (t_p),

V_{t_p} given by:

$$V_{t_p} = \left[\frac{\bar{S}_v}{S_p + \bar{S}_v}\right] n \quad . . . \text{(see equations 2-4)}$$

$$V = \text{traffic volume (vehicles/unit time)} = \frac{\left[\frac{\bar{S}_v}{S_p + \bar{S}_v}\right] n}{t_p}$$

or, since $t_p = \dfrac{D_{AB}}{S_p}$,

$$V = \frac{S_p}{D_{AB}} \left[\frac{\bar{S}_v}{S_p + \bar{S}_v}\right] n \quad . . . \text{(working equation)}$$

FIGURE 13. "SPEED RATIO" CONCEPT FOR TRAFFIC VOLUMES FROM STRIP AIRPHOTOS

If the plane is flying in the same direction as the vehicles in question, equation 23 becomes

$$V = \frac{S_p}{D_{AB}} \left[\frac{\bar{S}_v}{S_p - \bar{S}_v} \right] n \qquad \text{.......................Eq. 24}$$

The Automatic Ground Technique

Concept

The fully automated data gathering system is designed to mechanically or electrically detect and record traffic phenomena at a fixed location on the highway. Using pneumatic tube sensors and a multipen graphic recorder, this task is accomplished by a relatively simple procedure. A vehicle striking the flexible detector tube on the roadway causes air pressure within the tube to be built up against a diaphragm, forcing it to deflect. This movement is transmitted as an electrical impulse to the pen recorder which, in turn, converts the impulse back into mechanical energy, as evidenced by the deflection of a pen scribing on a continuously moving tape.

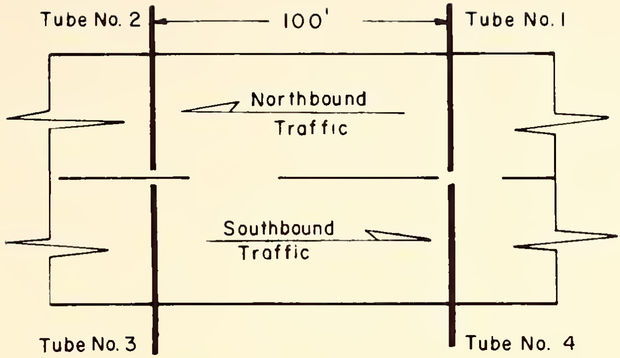
Speed is determined as a function of the time required for the vehicle to travel the fixed distance between two tubes. Headways and volumes may be obtained directly by linear measurements and counts from the calibrated data tapes.

Study Procedure

Pneumatic tube detectors and an Esterline Angus Model A.W. twenty pen graphic recorder were employed by R. C. Sonntag (76) for collecting volume, spot speed and arrival time data on various two lane, urban routes in Lafayette and Indianapolis, Indiana during the Spring of 1962. Data tapes obtained at a location on Indianapolis' Arlington Avenue were used in the present research on method efficiency. The procedure for setting up the equipment and collecting data has been adequately outlined by Sonntag; therefore, no attempt will be made to restate the details here (76).

Techniques for reducing data from the recorder tapes were essentially the same as developed by Sonntag. Vehicles were numbered in successive order of their recorded arrival at one of the two detector locations and irrespective of their direction of travel (see Figure 14). The sensor tubes having been placed a defined distance apart, each speed determination required only a measurement of the time it took the vehicle to travel this distance. Since the recording device employed for each detector a pen scribing on a moving tape, the measurement between impulses yielded time, in seconds, on a properly calibrated scale.

In the Arlington Avenue survey, the pneumatic tubes were placed 100 feet apart. When the tape was moved at 12 inches per minute, a 50 unit per inch engineers' scale permitted direct time readings (see Figure 14). Conversion into miles



LOCATION OF DETECTOR TUBES
ON THE ROADWAY

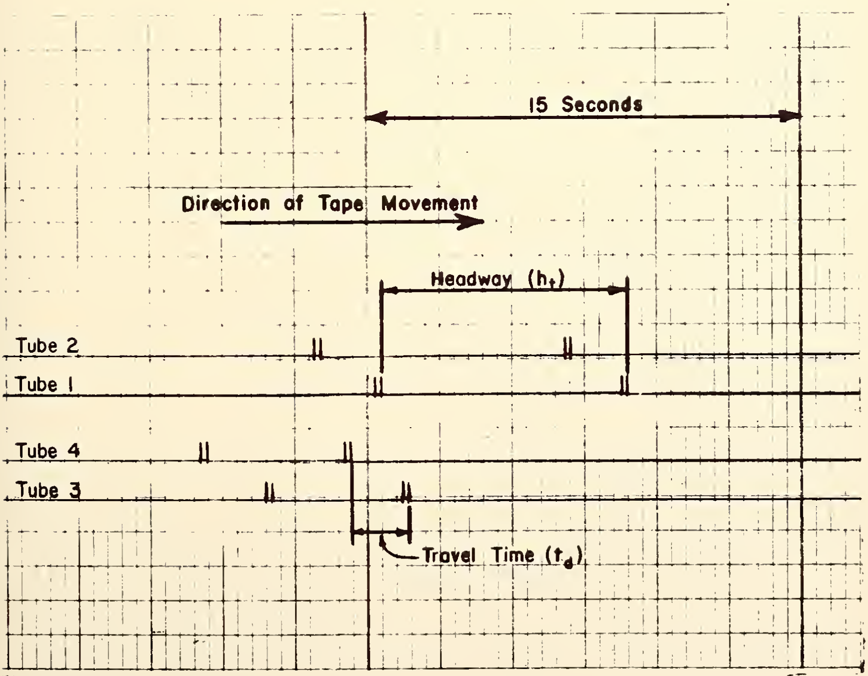


FIGURE 14. GRAPHIC PEN RECORDER TAPE

per hour was readily accomplished using the equation,

$$s_v = \frac{0.682d}{t_d}$$

where

s_v = vehicle speed in miles per hour

d = distance between tubes in feet

and

t_d = measured travel time in seconds

Each vehicle was also classified by direction and type. Vehicle type classification was based upon the number of axles counted, this being the only characteristic detected by the tubes. Thus, all two axle vehicles were classified as passenger cars, while those with three or more axles were assumed to be trucks.

Figure 14 depicts the simple technique used to obtain vehicle arrival times. After choosing a location on the tape to be designated as "0 minutes - 0.0 seconds" and selecting one of the two pen lines for each lane on which to measure, the scale was placed such that arrival times could be read directly. A subtraction of each arrival time from the one succeeding it yielded the desired time headways. For the purposes of this study, headways were tabulated irrespective of the direction of flow; however, the method is equally applicable to measurements by lane or direction.

Traffic volumes were counted directly from the number of vehicles striking a detector tube over a specified time period. Minute volumes, along with speeds and headways, were tabulated on data sheets as illustrated in Figure 15.

Traffic Flow Data

Site - Arlington Ave.
Time - 5:00 PM   Date - 6/8/62
Distance Between Tapes - 100'

Vehicle Number	Direction of Travel	Vehicle Type	Arrival Time	Travel Time(t_d)sec	Time Headway (h)	Minute Volume
1	S	Pass.	0'-3.6"	2.15	-----	
2	S	Pass.	0'-12.5"	2.60	8.9 sec.	
3	S	Pass.	0'-23.8"	2.25	11.3	
4	N	Pass.	0'-24.3"	2.45	0.5	
5	S	Pass.	0'-28.5"	2.30	4.2	
6	N	Pass.	0'-33.0"	2.75	4.5	
7	N	Pass.	0'-52.0"	2.05	19.0	
8	N	Pass.	0'-57.1"	2.35	5.1	
9	S	Pass.	0'-58.8"	2.15	1.7	9
10	N	Pass.	1'-0.1"	1.90	3.0	

' = min.

" = sec.

FIGURE 15. VEHICLE SPEED, TYPE AND HEADWAY DATA SHEET FOR PEN RECORDER

THE STUDY SITES

Site Selection

Aerial Photography Study

Tangent, level highway locations, generally multilane*, divided and one to two miles in length, were selected for study by time-lapse aerial photography. In order to minimize the number of flight runs required and to study flow characteristics at high traffic densities, routes with high peak hour volumes were sought. These routes were in Indiana so as to facilitate field trips to the sites. In addition, a minimum of obstruction to a vertical view of the travel lanes and the absence of traffic control devices in the study section were desired.

Automatic Graphic Recorder Study

Sites suitable for use of the pneumatic detector tubes and Esterline Angus pen recorder were chosen by R. C. Sonntag (76). The basic condition for selection was that the route be a two-lane urban or suburban collector or arterial street.

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* All sites were multilane except for the two-lane route studied in common with R. C. Sonntag (76).

The tubes were located in a tangent section of at least one mile in length with a minimum of major hindrances to the flow of traffic.

Site Description

Following an extensive search in central and northwestern Indiana, five sites were chosen for study by the automatic tube-recorder method and/or the time-lapse aerial photography technique. These routes are described in some detail below.

Tri-State Expressway, between the Calumet Avenue and Indianapolis Boulevard Interchanges, Hammond, Indiana (Aerial photography study)

This suburban stretch of four-lane divided freeway is a part of Indiana's link in the Tri-State Expressway between Illinois and Michigan. The one-mile, level, tangent stretch of roadway extending eastward from the Calument Avenue interchange to approximately 0.3 miles west of the Indianapolis Boulevard exit was chosen for study (see Figure 16). The topography of the area is flat and the site is free of obstruction to the vertical view save for an overpass at Columbia Avenue. The section is situated on a 250-foot right of way and is completely free of access and egress points. Portland cement concrete pavement is employed with expansion joints at 40-foot intervals. The four 12-foot travel lanes

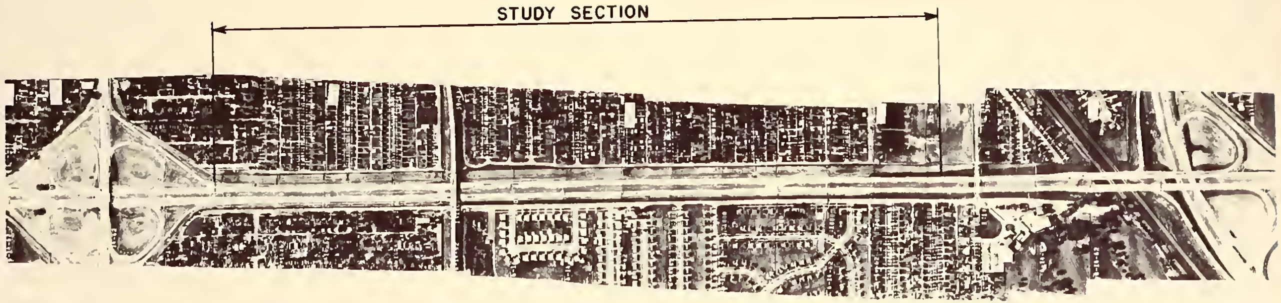

FIGURE 16. TRI-STATE EXPRESSWAY, HAMMOND

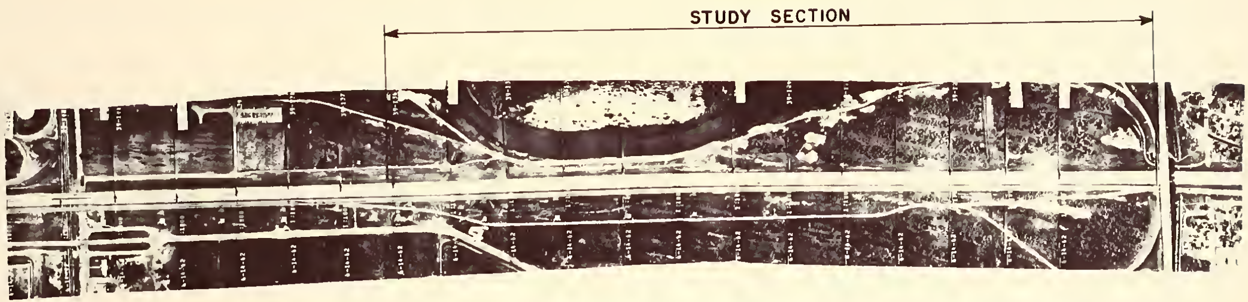

FIGURE 17. EAST-WEST TOLL ROAD, HAMMOND

lie astride a 50-foot grass median with the outside lanes being bordered by 11-foot gravel shoulders. The roadway is well maintained and possesses good rideability characteristics.

From volume counts taken at the site in April, 1962, the period from 4:30 to 5:30 PM was judged to have the peak afternoon eastbound traffic flow (1700 vph), with approximately 15 percent being trucks. At no time, however, did the traffic cease to be free moving. Passenger car and bus speed limits are posted at 65 mph while the maximum for trucks in excess of 2½ tons is 55 mph. Informally applying the "average car" technique, the mean speed for the eastbound evening peak hour traffic was observed to be about 55 mph.

Indiana East-West Toll Road, between Kennedy Avenue
and Cline Avenue, Hammond, Indiana
(Aerial photography study)

The Indiana Toll Road is a modern, four-lane divided highway with complete control of access. The level, tangent section under study extends, free of any interchange points, from the overpassing Cline Avenue and Chicago South Shore and South Bend Railroad bridges westward to about 0.4 miles east of where the route is underpassed by Kennedy Avenue (see Figure 17). The roadway pierces an industrial area in

the flat, beach ridge country of northwestern Indiana and is completely free of obstruction to the aerial view.

A 4-foot concrete median and two 8-foot stabilized shoulders divide the four 12-foot travel lanes. The lanes, affording excellent rideability, are surfaced with Portland cement concrete with joints at 60-foot spacings. Nine-foot wide stabilized shoulders adjoin the outside lanes. Passenger vehicle speed limits are set at 60 mph while trucks are limited to 55 mph.

Late afternoon and early evening traffic counts in April, 1962 revealed that the Toll Road has only light to moderate volumes during the traditional "peak hours". The route's eastbound flow appeared to reach a maximum between 5:00 and 6:00 PM.

Shadeland Avenue, State Route 100, between 10th and 21st Streets, Indianapolis, Indiana

(Aerial photography study)

Located nearly six miles from downtown Indianapolis, this route serves as an east-side bypass around the city in addition to being a major arterial permeating a suburban area of light industry, commercial activity, and middle-class residences. The level, tangent study site is bounded by 10th and 21st streets in a location primarily residential in character (see Figure 18). Foliage in the vicinity of the right-of-way offers little or no obstruction of the travel lanes to overhead views.

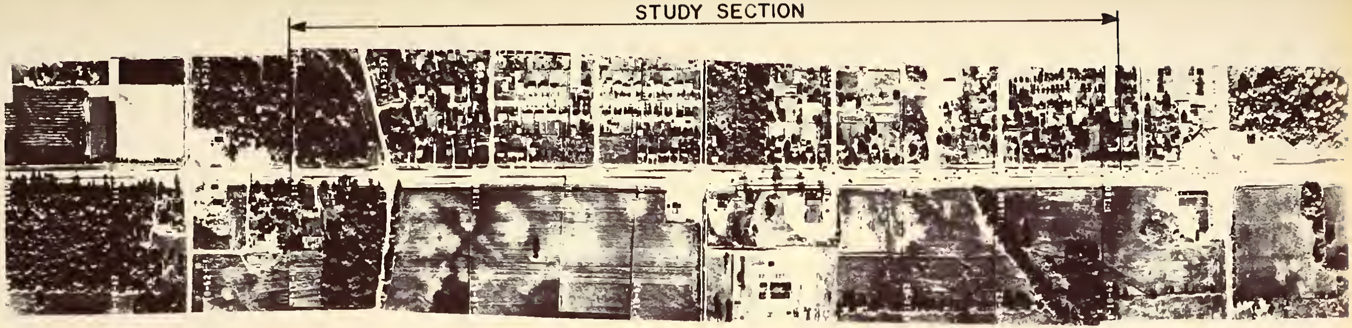

FIGURE 18. SHADELAND AVENUE (S.R. 100), INDIANAPOLIS

SOUTH

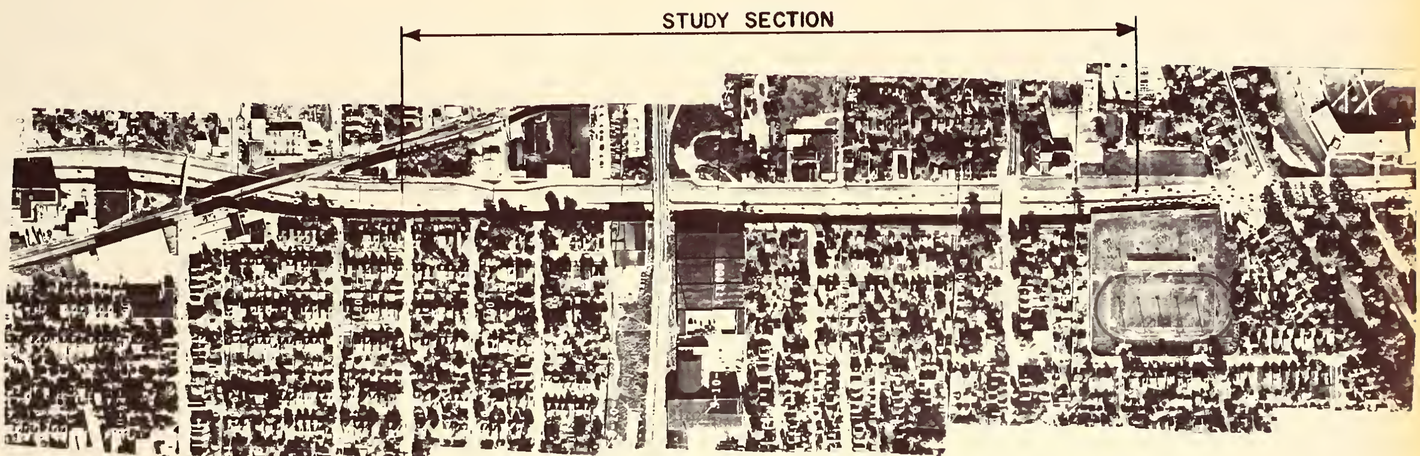

FIGURE 19. MADISON AVENUE (U.S. 31), INDIANAPOLIS

SOUTH

More than a score of curb cuts, ranging from private drives to intersecting local and collector streets, dot the northbound lanes while southbound traffic is offered relatively few access or egress points. Left turn maneuvers are made from lanes placed within the 15-foot grass median. Traffic control devices are limited to the signalized intersections at 10th and 21st Streets, but were observed to cause flow congestion and stagnation at the extremities of the study site.

The roadway consists of four 12-foot travel lanes with gravel and earth shoulders of varying width. Portland cement concrete pavement jointed at 40-foot intervals predominates and the surface is in good condition. A posted speed limit of 40 mph governs all traffic. "Average car" runs over the route indicated a mean speed of 40 mph during periods of peak but uncongested flow. Traffic counts revealed that the evening peak occurs between 4:45 and 5:30 PM with first the southbound and later the northbound traffic representing the major streams. The southbound movement is sparked by the exodus of workers from factories north of the study section. Northbound traffic increases as commuters from Indianapolis and shoppers leaving the East Gate Shopping Center begin their homeward trips. Truck traffic was found to constitute less than three percent of the route's rush hour volume.

Madison Avenue, U. S. Route 31, between Pennsylvania Railroad Bridge and Pleasant Run Parkway, Indianapolis, Indiana

(Aerial photography study)

Madison Avenue, U. S. Route 31, takes on many guises over its length immediately south of downtown Indianapolis. The site under investigation possesses urban freeway characteristics with complete control of access and a 14-foot wide grass medial strip*. Six lanes wide, the study section extends along a level tangent for 0.7 miles from a signalized intersection with the Pleasant Run Parkway north to 0.1 miles south of the overhead, two-track through girder bridge of the Pennsylvania Railroad (see Figure 19). Southbound flow patterns are influenced by a traffic signal 0.2 miles north of the railroad bridge. Obstructing an aerial view of the travel lanes are a bridge of the Indianapolis Union Railroad and the Raymond Street overpass.

The six 12-foot lanes are surfaced in Portland cement concrete with joints at 40-foot intervals, and are maintained in excellent condition. The roadway is devoid of shoulders but is paralleled by 5½-foot sidewalks. All traffic is subject to a 45 mph speed limit. Test car observations

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* The median narrows at the north end of the study section into a concrete barrier.

indicated an average speed of 35 mph for uncongested peak hour flow. Recent weekday traffic counts pinpointed the route's southbound evening peak volume (2700 vph) as occurring between 4:45 and 5:30 PM. At maximum volumes, the Pleasant Run Parkway signal was observed to cause vehicle backups extending well into the study section. During the early evening hours truck traffic accounts for about one percent of the total southward movement.

Arlington Avenue, between 38th and 46th Streets,
Indianapolis, Indiana
(Aerial photography and graphic recorder studies)

Serving as both a collector and minor arterial, Arlington Avenue permeates a rapidly growing residential area nearly 5 miles east of downtown Indianapolis. The site investigated is a level, tangent section extending north from the signalized intersection at 38th Street to that at 46th Street, a distance of one mile. The roadway's cross section is comprised of two 11-foot cement concrete travel lanes bounded by occasional stretches of earth shoulder on which parking is permitted. Curb cuts for private driveways and intersecting local streets are frequent, and a number of bus stops are encompassed in the study section. A moderate amount of tree foliage results in some restriction on the aerial view of the lanes.

Recent spot speed studies (76) yielded an average vehicle velocity of 30 mph during the evening rush hours. Maximum weekday afternoon volumes occur at about 5:00 PM during the homeward trek of the City's commuters.

SOME TRAFFIC FLOW RELATIONSHIPS STUDIED WITH TIME-LAPSE AERIAL PHOTOGRAPHY

Nearly five hundred standard aerial photographs were taken in this research. Although the design of the experiment did not permit a thorough analysis of any particular traffic characteristic or highway site, a wealth of information revealed itself on the aerial exposures. The following pages graphically illustrate the wide variety of traffic flow relationships which one may effectively study with the aid of intermittent aerial photographs. It is emphasized, however, that these relationships are based upon a limited amount of data and should not be considered conclusive.

To be accepted by highway officials as a useful means of collecting traffic data, the photographic procedures must be capable of yielding basic information on traffic speeds, headways and volumes. Figure 20 depicts a cumulative frequency graph of individual vehicle speeds compiled from intermittent aerial exposures of the Tri-State Expressway. The data were gathered over a one-mile homogeneous section of the highway so as to afford information comparable to a "spot" speed study. The vehicle speeds of Figure 20 were plotted for several directional volumes to illustrate the

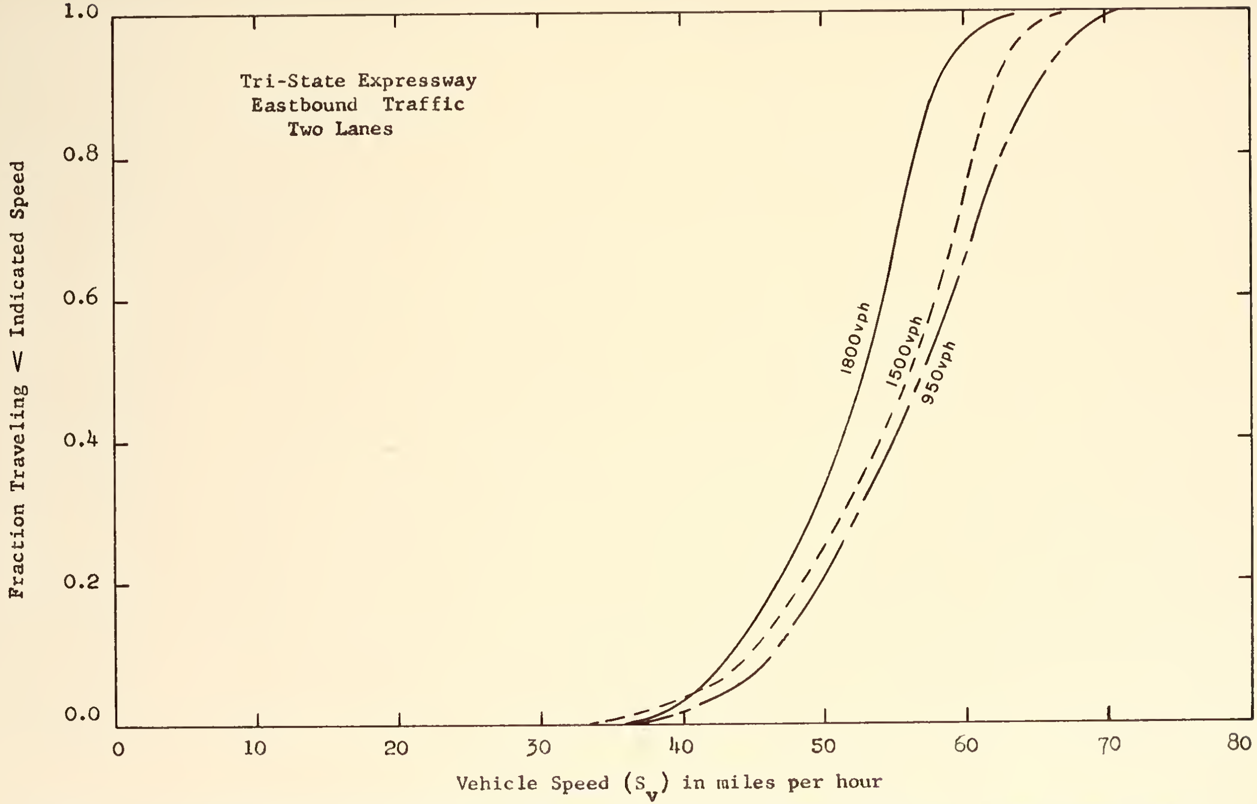

FIGURE 20. VEHICLE SPEED DISTRIBUTION AT VARIOUS DIRECTIONAL TRAFFIC VOLUMES ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

tendency for velocities to decrease in magnitude and range with increasing traffic.

Many investigators have noted that average speed tends to vary as a function of the traffic volume. Mean speeds for various directional volumes of traffic on the Tri-State Expressway are shown in Figure 21, along with a best fitting straight line constructed by the method of least squares*. Only 45 percent (r^2) of the observed variation in speed could be explained by the simple linear regression equation. In addition, for a standard F test at the 0.1 level of significance (α), the slope of the regression equation was not found to differ significantly from zero. Thus, mean vehicle speeds on this four-lane freeway were not found to be a function of directional traffic volume within the range of 950 to 2100 vehicles per hour.

Cumulative frequency distributions of time headways for two lanes of unidirectional traffic at three different free-flowing volumes were constructed from the Tri-State Expressway photography (see Figure 22). A comparison of these curves with the Poisson distribution** seemed to confirm Adams' (1) contention that vehicles are randomly distributed on the open highway. Some tendency was noted for more long headways to occur at a given volume than could be attributed

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* See Appendix E for a discussion of the statistical terms and procedures employed in this section.

** See Appendix E for a discussion of the Poisson theory of probability.

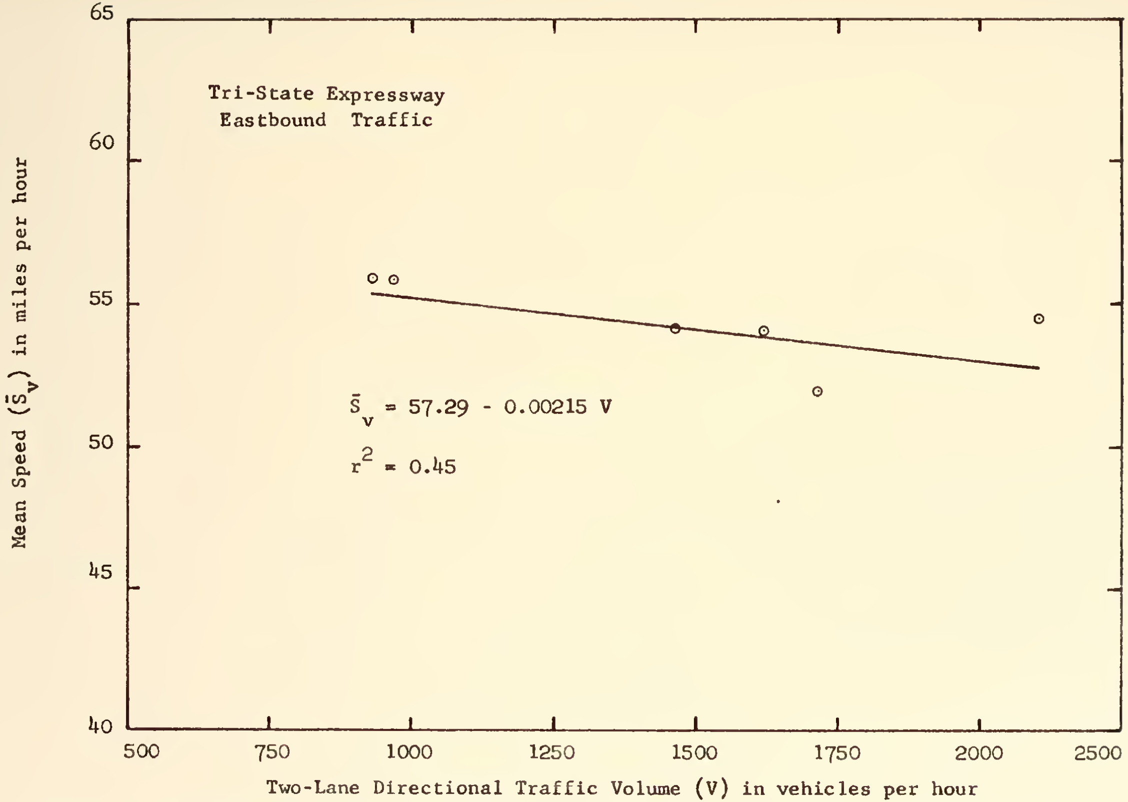

FIGURE 21. MEAN SPEED AS A FUNCTION OF DIRECTIONAL TRAFFIC VOLUME ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

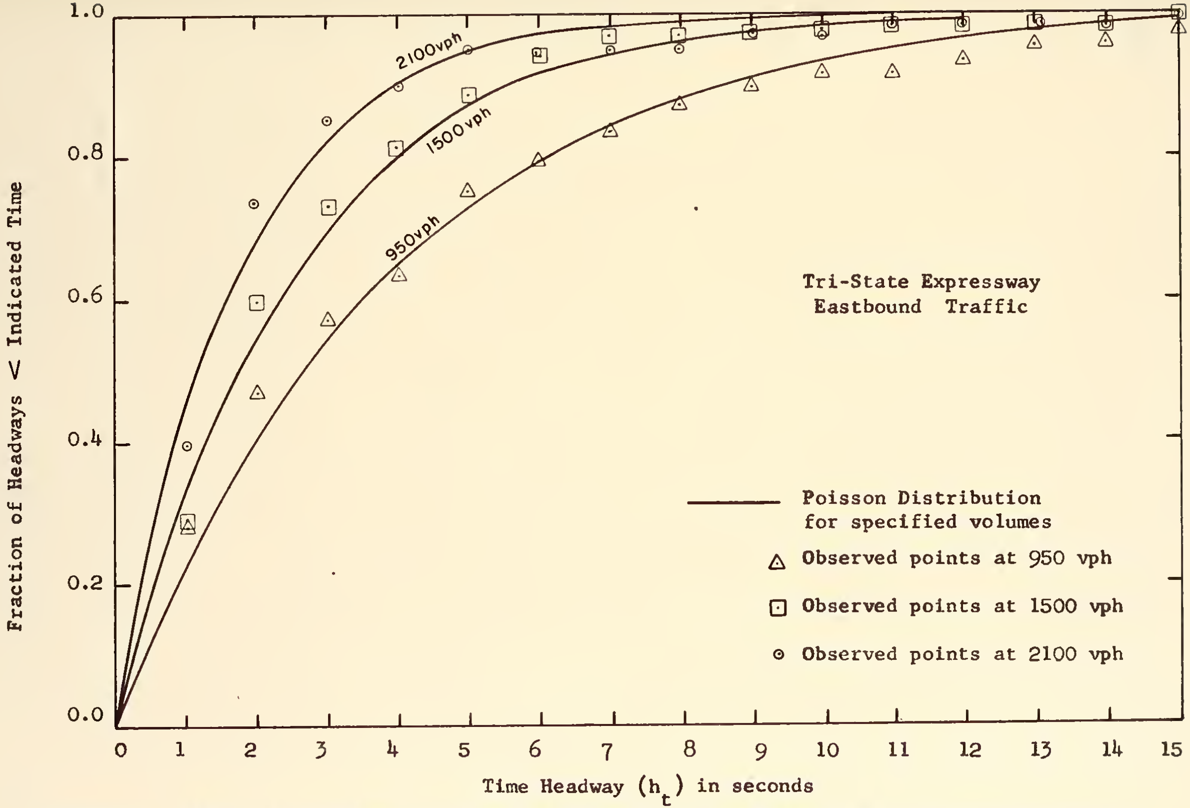

FIGURE 22. CUMULATIVE FREQUENCY DISTRIBUTION OF VEHICLE TIME HEADWAYS AT VARIOUS DIRECTIONAL VOLUMES ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

to random events. This was probably due to the entrance onto the expressway of a few slow moving vehicles at the Calument Avenue interchange. As expected, the frequency of short headways increased with mounting traffic volumes.

The speeds of individual vehicles moving freely at specified time headways behind vehicles in the same lane were investigated and the mean value plotted for the Tri-State Expressway (see Figure 23). A simple linear equation was fitted to the observed points but yielded an r^2 of only 0.10. Similarly, Figure 24 depicts a mean speed versus time headway plot for traffic on the six-lane Madison Avenue site. An r^2 of 0.31 was computed for the associated regression line. For both sites, the slope of the regression line did not test significant at the 0.1 level. Therefore, whereas the Highway Capacity Manual (13) reports a decrease in vehicle speeds proportional to h_t less than 8 seconds, no such conclusion was reached in the present research.

When studying highway capacity on multilane facilities, the investigator is often interested in lane usage characteristics. Figure 25 relates the number of vehicles per hour traveling in the median, or passing, lane as a fraction of the total, two-lane directional volume. A linear regression equation was computed for the observed points and a relatively high r^2 of 0.69 was noted. Since the slope of the line tested to be positive at a 0.1 level of significance, it was concluded that the portion of the total flow to be found in the median lane varied directly with the directional volume

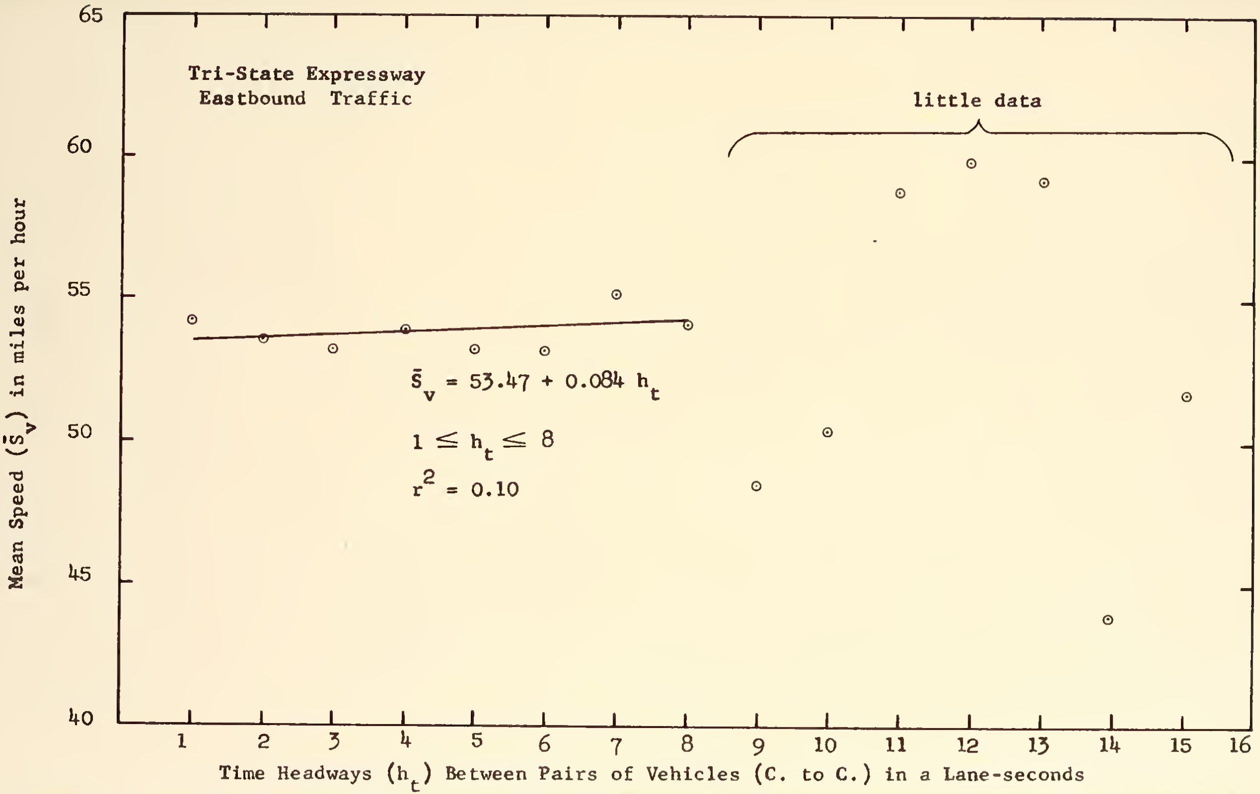

FIGURE 23. SPEED OF VEHICLES TRAVELING AT GIVEN TIME HEADWAYS BEHIND PRECEDING VEHICLES ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

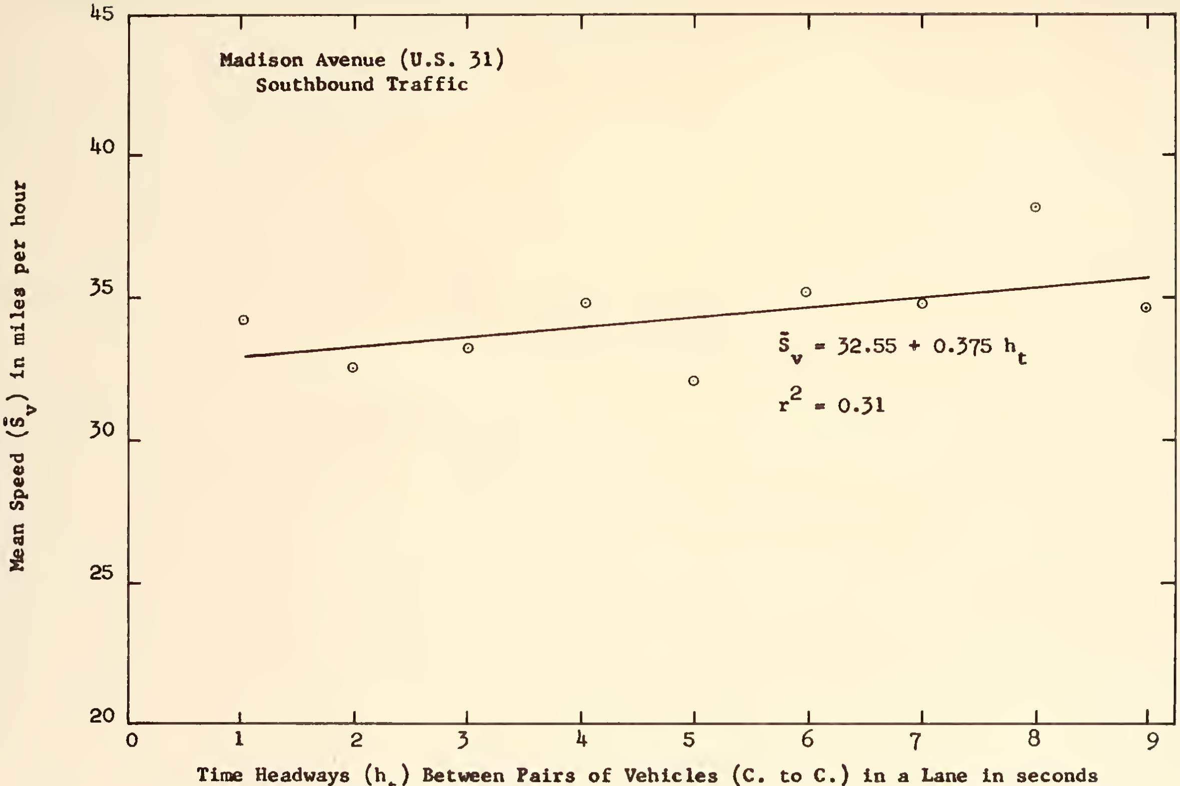

FIGURE 24. SPEED OF VEHICLES TRAVELING AT GIVEN TIME HEADWAYS BEHIND PRECEDING VEHICLES ON A SIX-LANE DIVIDED HIGHWAY AS MEASURED ON AERIAL PHOTOGRAPHS

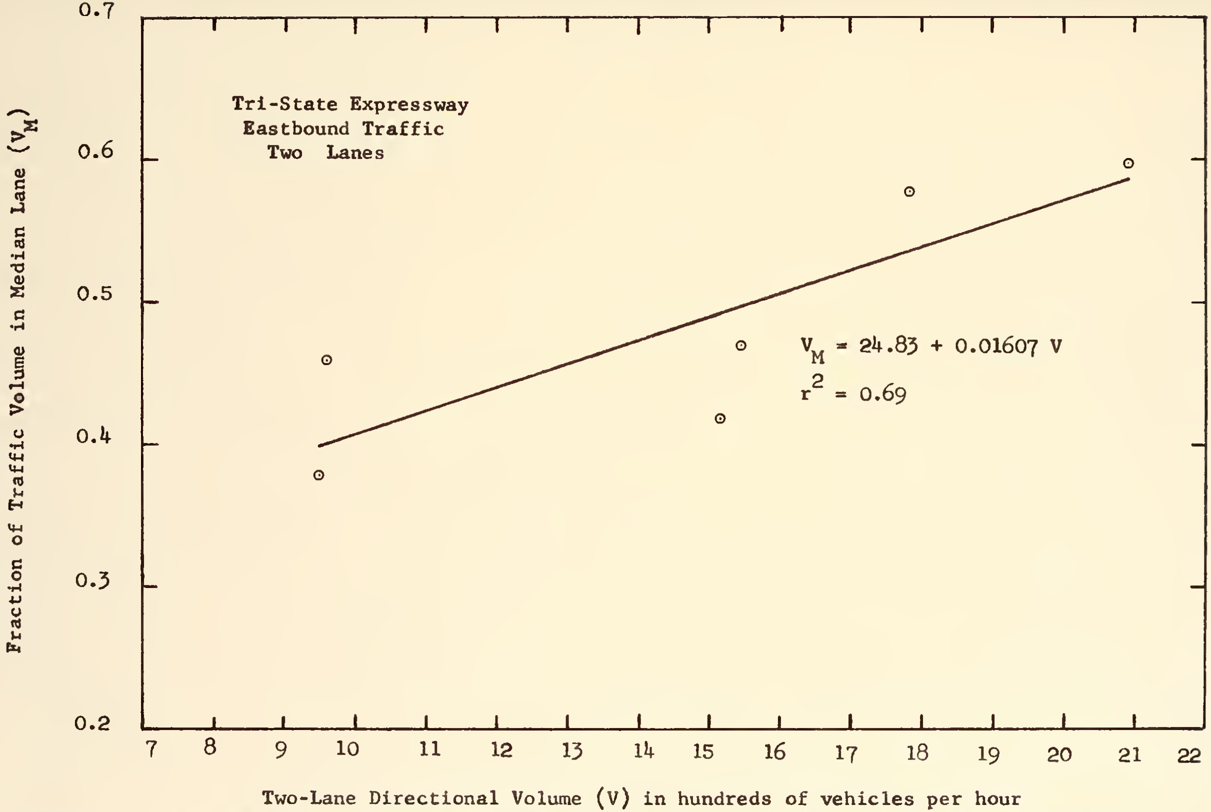

FIGURE 25. FRACTION OF THE DIRECTIONAL TRAFFIC VOLUME IN THE MEDIAN LANE AT VARIOUS VOLUMES ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

for the range of 950 to 2100 vph. However, it is expected that the distribution of traffic by lane would vary from route to route as a function of the physical characteristics of the site.

Southbound volumes on the six-lane Madison Avenue expressway were distributed as graphed in Figure 26. The regression line for the median lane had a significant (at $\alpha = 0.1$) positive slope and an r^2 of 0.58. On the other hand, a smaller fraction of the total flow was found in the middle lane as directional volume built up. The negatively sloped regression line for the middle lane accounted for 45 percent of the variation in lane usage for the volumes considered. On the other hand, virtually no variance in the percent of traffic traveling in the outside lane could be attributed to directional volume or associated with linear regression.

The preceding discussion has been confined to relationships involving only the basic traffic flow quantities of speed, volume and time headway. Several investigators (35, 39, 80, et al.) have suggested the use of "spacial" variables as being more meaningful and accurate representations of traffic flow phenomena. Data for two of these variables - traffic density and acceleration - are readily obtained with time-lapse aerial photography.

Wagner and May (80) have suggested a graphical method for pin-pointing, in terms of traffic density, locations along an extended length of roadway which are particularly

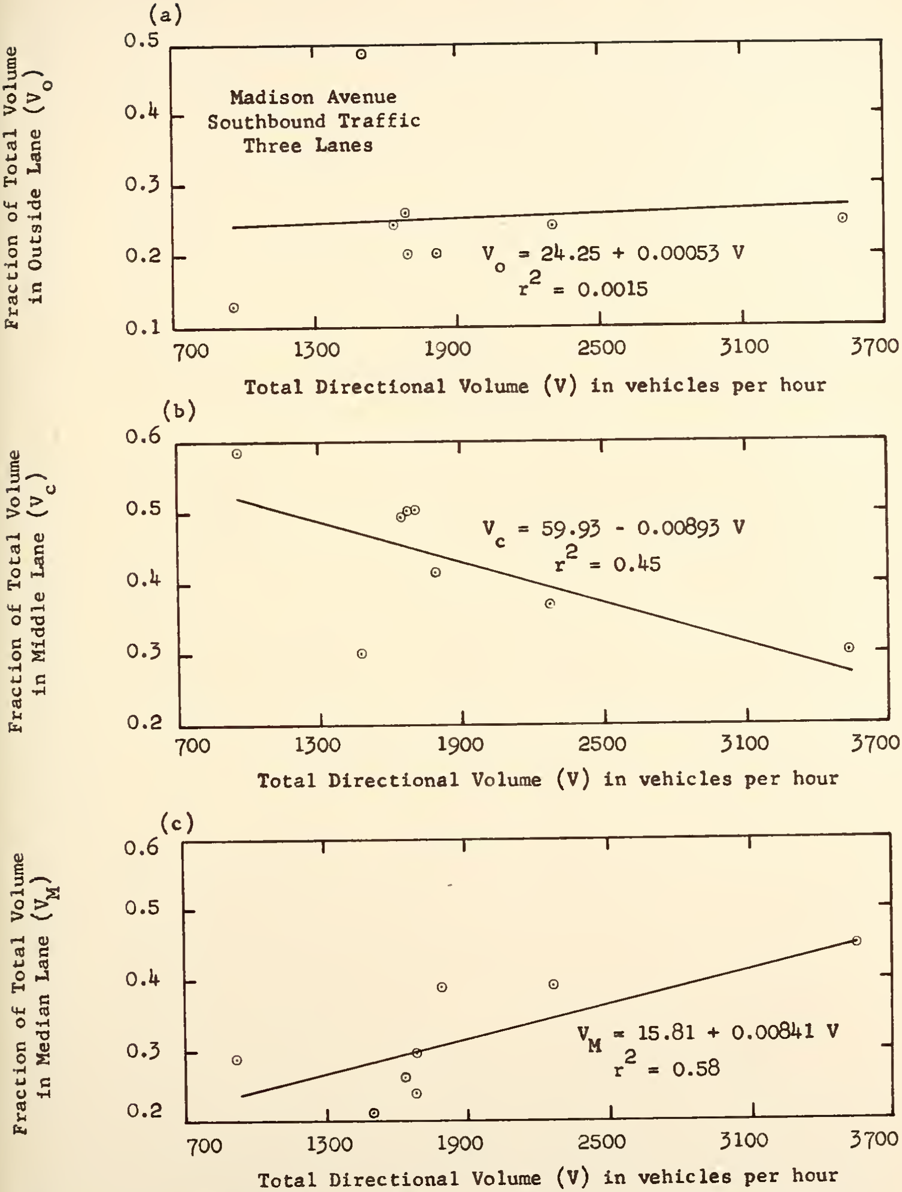

FIGURE 26. DISTRIBUTION OF TRAFFIC BY LANE AT VARIOUS VOLUMES ON A SIX-LANE DIVIDED HIGHWAY AS MEASURED ON AERIAL PHOTOGRAPHS

susceptible to congestion, and to determine, in units of time, the duration of these high density conditions. Utilizing time-lapse vertical photography, flight runs were made over the route at intervals of 5 to 15 minutes throughout the study period. Every exposure afforded a density for each direction of traffic. Since the scale of photography was known, this quantity could be expressed as vehicles per lane-mile (vplm):

$$\text{Density (vplm)} = P = \frac{\text{vehicle count for one direction of traffic}}{\text{miles of highway per exposure} \times \text{number of lanes}}$$

These densities were plotted as functions of time and distance much as one would construct a topographic contour map. First, coordinates for the time of day and distance from a specified point were established. The traffic densities were then denoted in the appropriate places on the rectangular grid as shown in Figure 27. Connecting points of equal density, the figure's overlay depicts contour lines at intervals of 20 vplm.

For the Madison Avenue example illustrated, high densities, indicative of extreme congestion, occurred near the Pleasant Run Parkway signalized intersection. This condition was particularly severe at about 5:30 PM when vehicles were backed up nearly 1000 feet. The roadway curvature and overhead bridges represented at the extreme right of the diagram appear to have been the source of moderate congestion in that area.

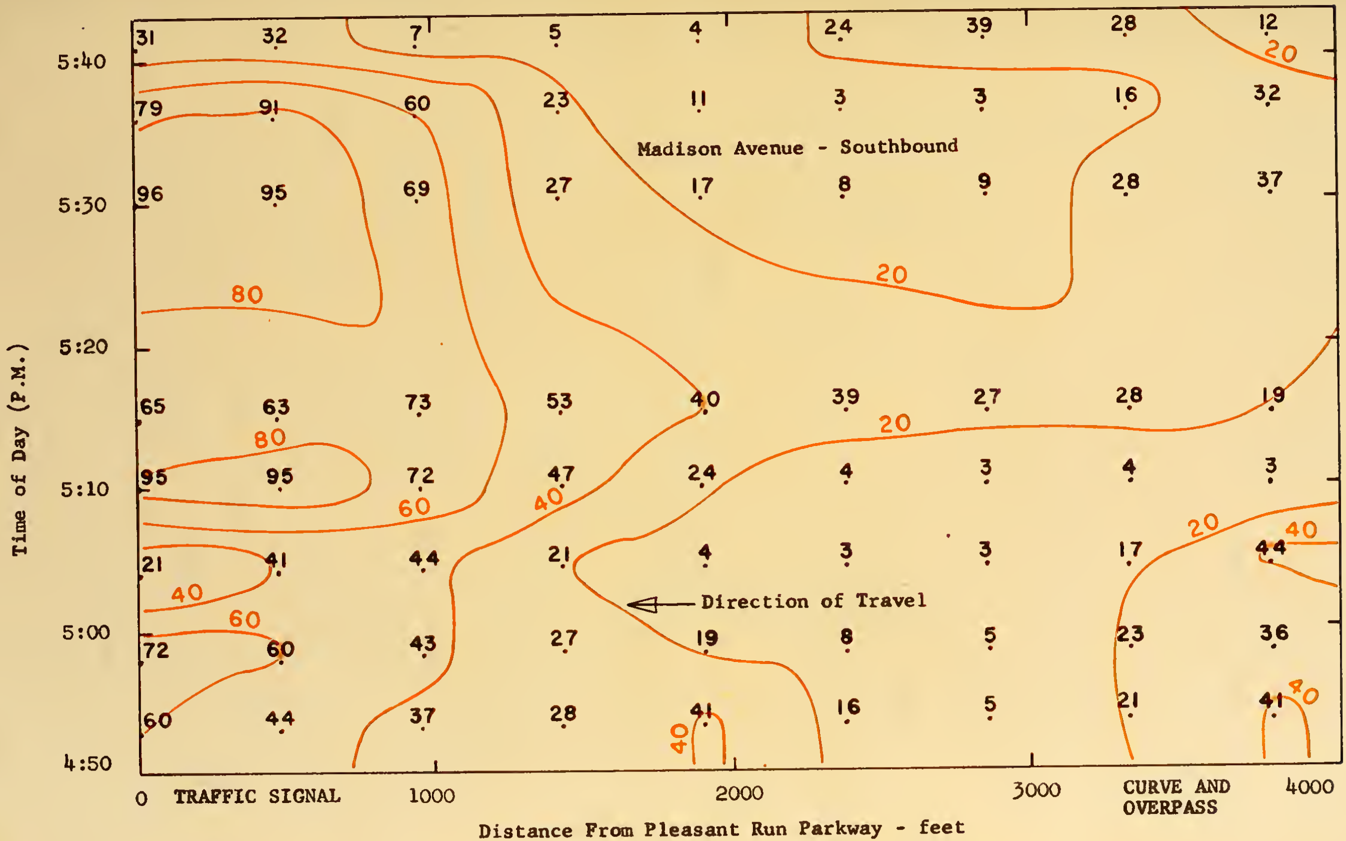

FIGURE 27. TRAFFIC DENSITY CONTOUR MAP PREPARED FROM AERIAL PHOTOGRAPHY

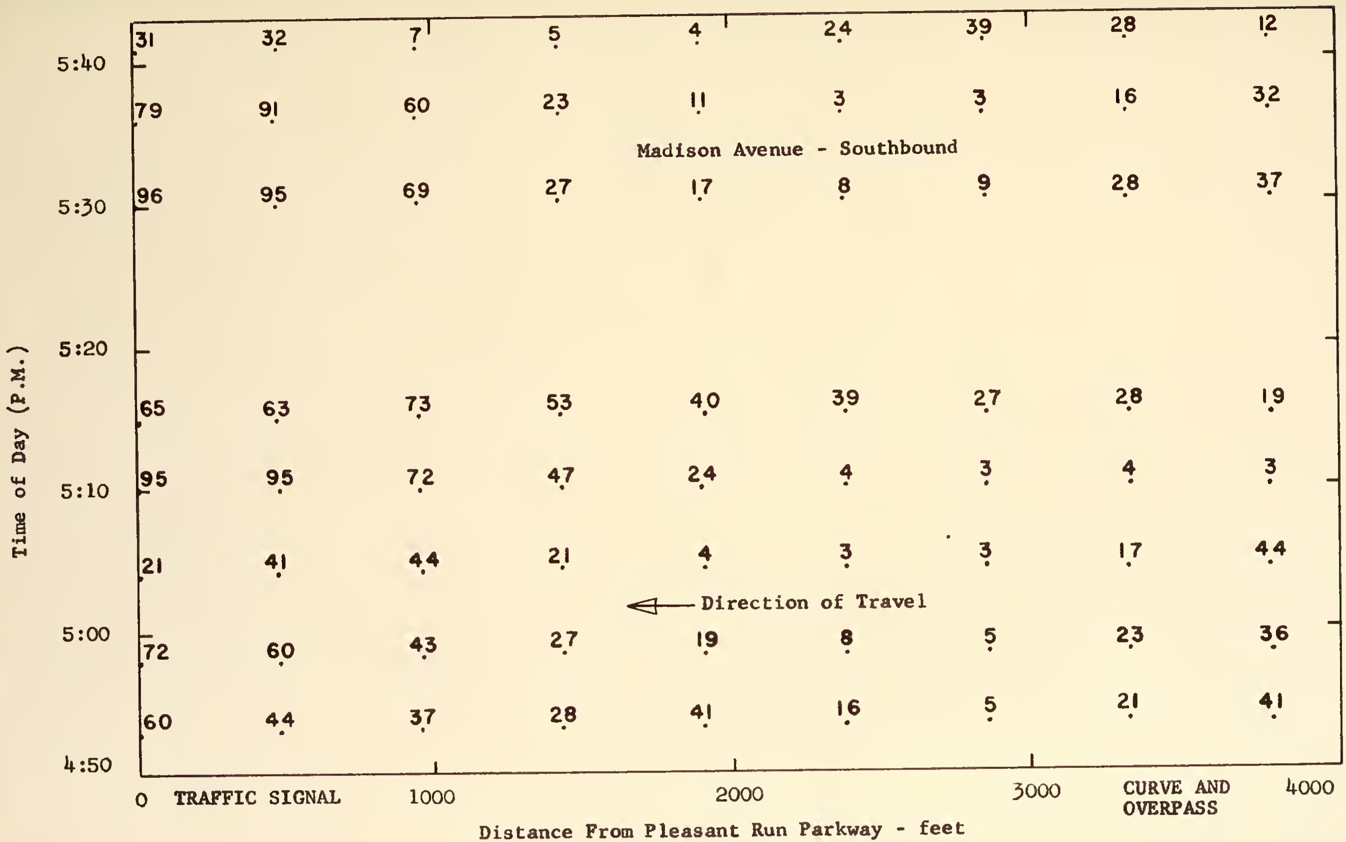

FIGURE 27. TRAFFIC DENSITY CONTOUR MAP PREPARED FROM AERIAL PHOTOGRAPHY

Figures 28 and 29 present mean speed as a function of route density for the Tri-State Expressway and Madison Avenue respectively. Once again, traffic densities were recorded on aerial exposures and converted into vehicles per mile (all lanes in one direction) or vehicles per lane-mile for analysis. Eastbound traffic on the Tri-State Expressway is the subject of Figure 28a. A simple regression line was fitted by the method of least squares and found to account for 24 percent of the observed variation in mean speed at densities between 4 and 56 vehicles per mile (vpm). At $\alpha = 0.1$, the line's negative slope tested significant.

When analyzed by individual lanes (Figures 28b and 28c), the linear decline in speed with increasing density tested significant and supported r^2 values of 0.54 and 0.59 for the outside and median lanes respectively. Likewise, regression lines fitted to Madison Avenue's "by lane" data yielded negative slopes which tested significant at the 0.1 level (see Figures 29a, b, c). The associated r^2 values were 0.24, 0.56 and 0.55 for the outside, middle and median lanes respectively. Considering all three lanes together, the resulting regression equation afforded an r^2 of 0.35 (see Figure 29d). However, variations in speed as a linear function of density were not significant at $\alpha = 0.1$.

Although traffic density is a function of both speed and route volume, it alone cannot adequately describe the nature of vehicle flow. At any given density, the facility may be either approaching congestion or emerging from congestion.

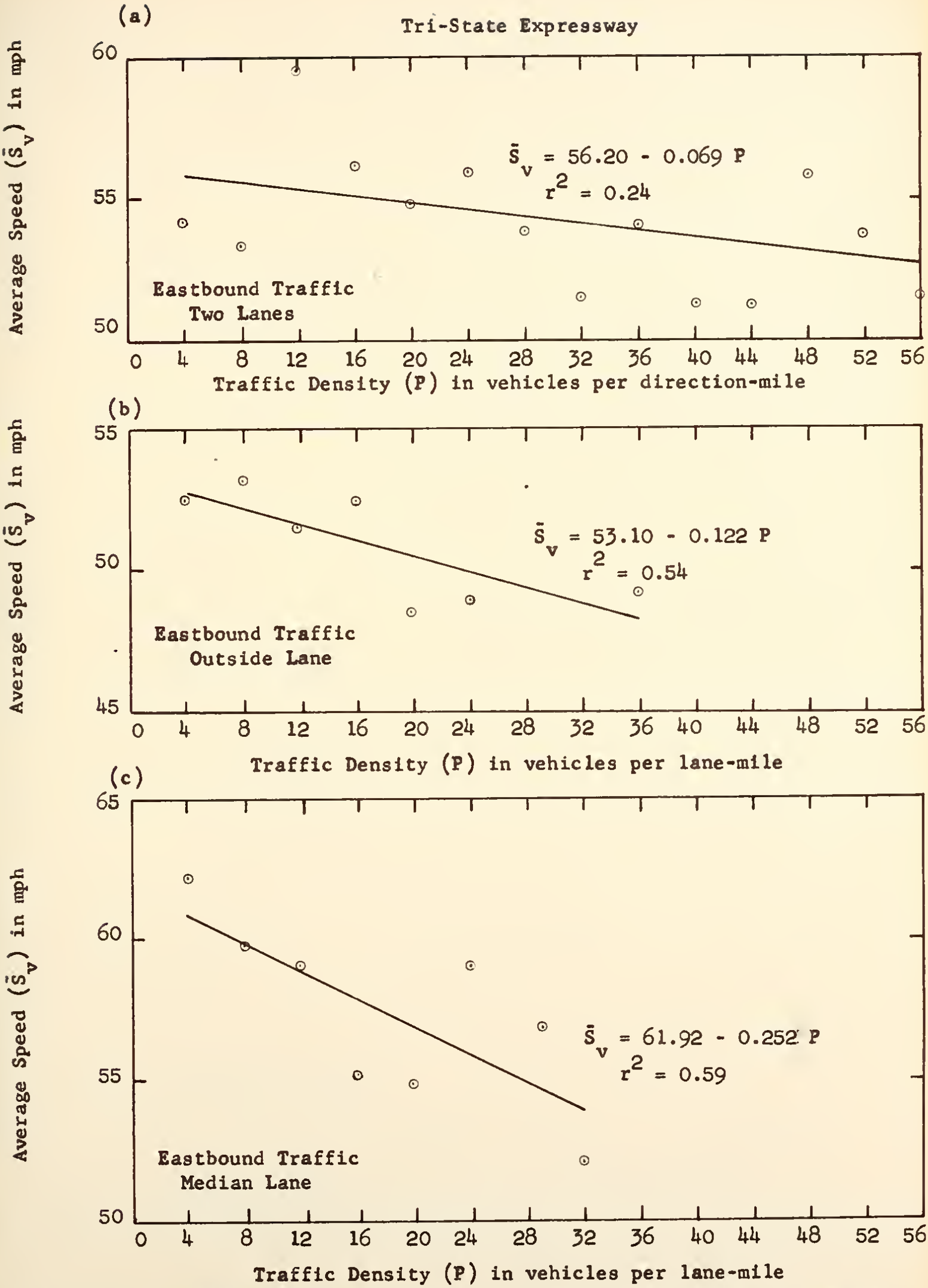

FIGURE 28. SPEED-DENSITY RELATIONSHIPS ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

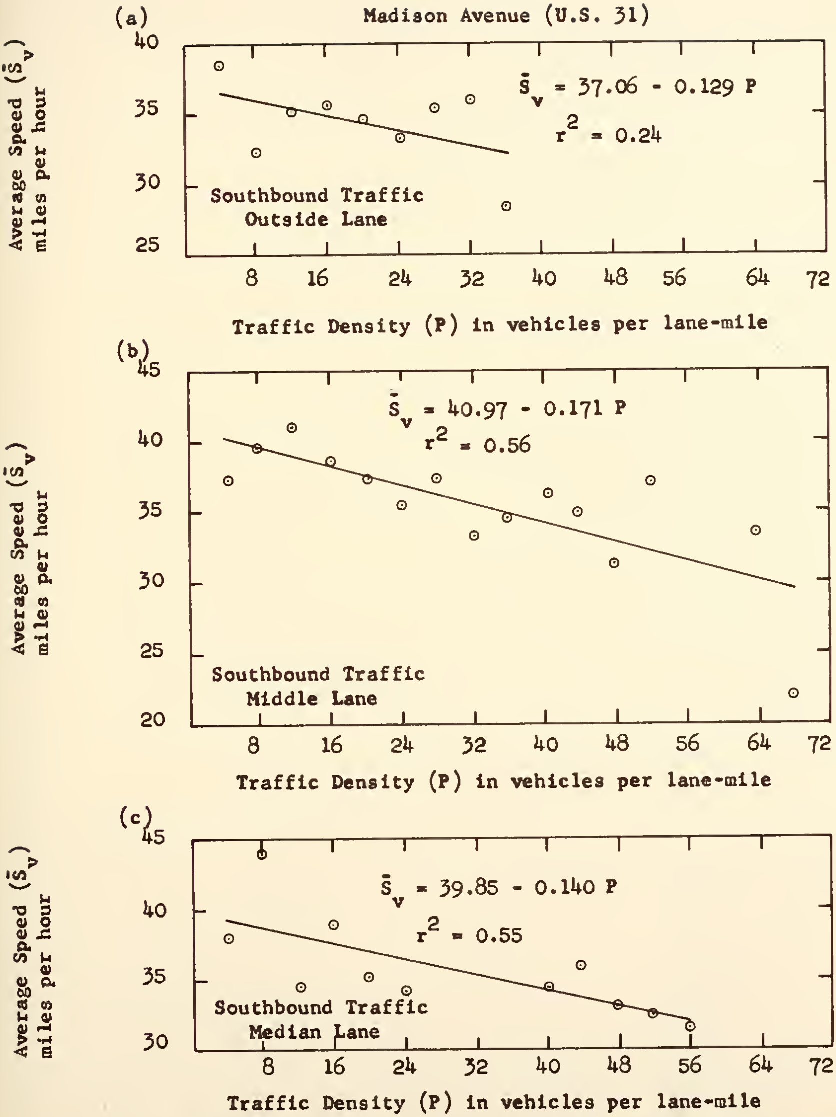

FIGURE 29. SPEED-DENSITY RELATIONSHIPS ON A SIX-LANE DIVIDED HIGHWAY AS MEASURED ON AERIAL PHOTOGRAPHS

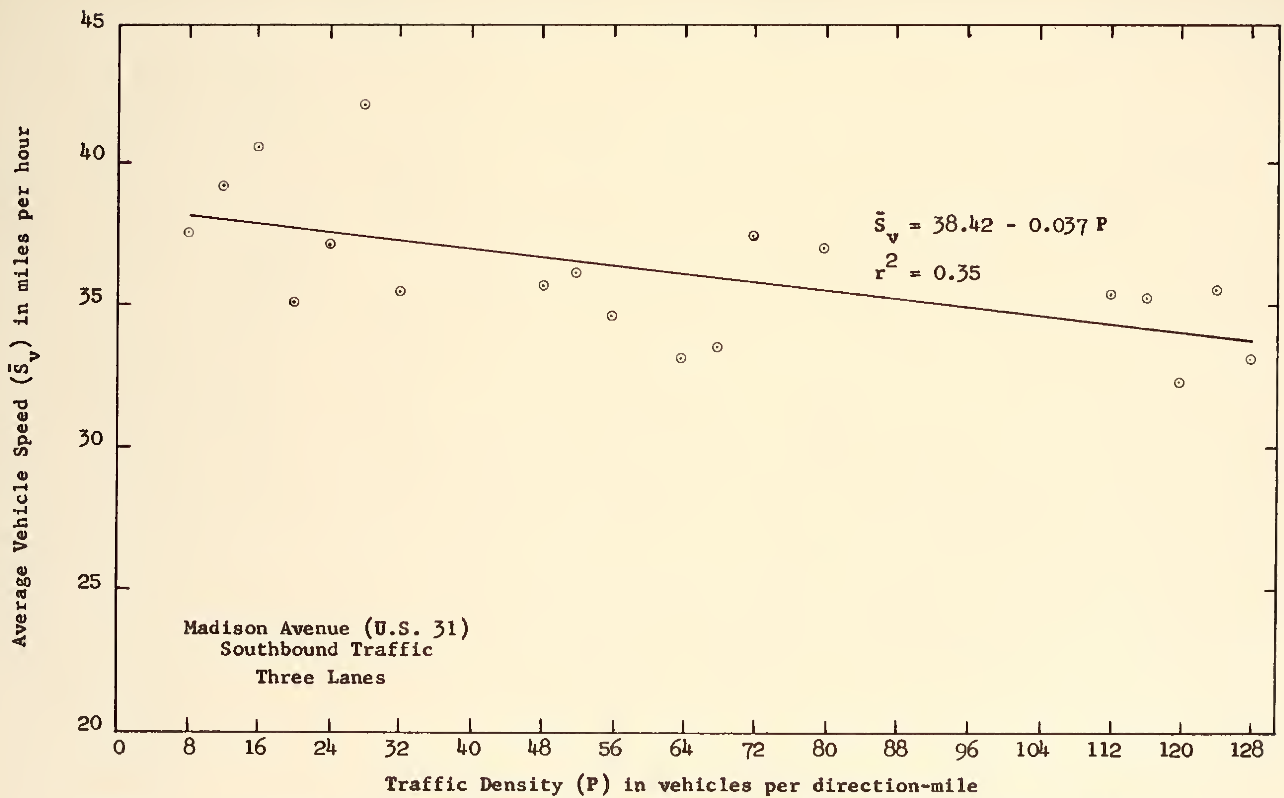

FIGURE 29d. SPEED-DENSITY RELATIONSHIPS ON A SIX-LANE DIVIDED HIGHWAY AS MEASURE ON AERIAL PHOTOGRAPHS

This dynamic component of traffic flow is probably best described by vehicle acceleration patterns. A net acceleration of vehicle speeds foretells a decrease in density, while the absence of acceleration reveals an unchanging density, and a net deceleration (negative acceleration) is indicative of increasing density.

The time-lapse aerial photography technique is an ideal means for observing the acceleration patterns of individual motorists as they progress along the highway. Figure 30 diagrammatically depicts the variations in speed for each of five vehicles traveling westbound on the Tri-State Expressway. Although in this example no vehicle was tracked for more than 2500 feet, longer traces could have been achieved by minimizing the speed of the aircraft relative to the vehicle's velocity and/or by increasing the flight elevation.

Figure 31 relates the positions of the five vehicles in point of time as well as space. Each vehicle's movement is represented by a line with the slope being a measure of speed as expressed in the equation,

$$\text{Tan } \theta = \frac{\Delta \text{ distance}}{\Delta \text{ time}} = \text{vehicle speed}$$

Changes in slope (speed) yield vehicle acceleration:

$$\frac{\Delta \text{ Tan } \theta}{\Delta \text{ time}} = \frac{\Delta \dfrac{\Delta \text{ distance}}{\Delta \text{ time}}}{\Delta \text{ time}} = \text{vehicle acceleration}$$

Lines crossing one another indicate that the vehicles in question were at the same longitudinal location on the highway

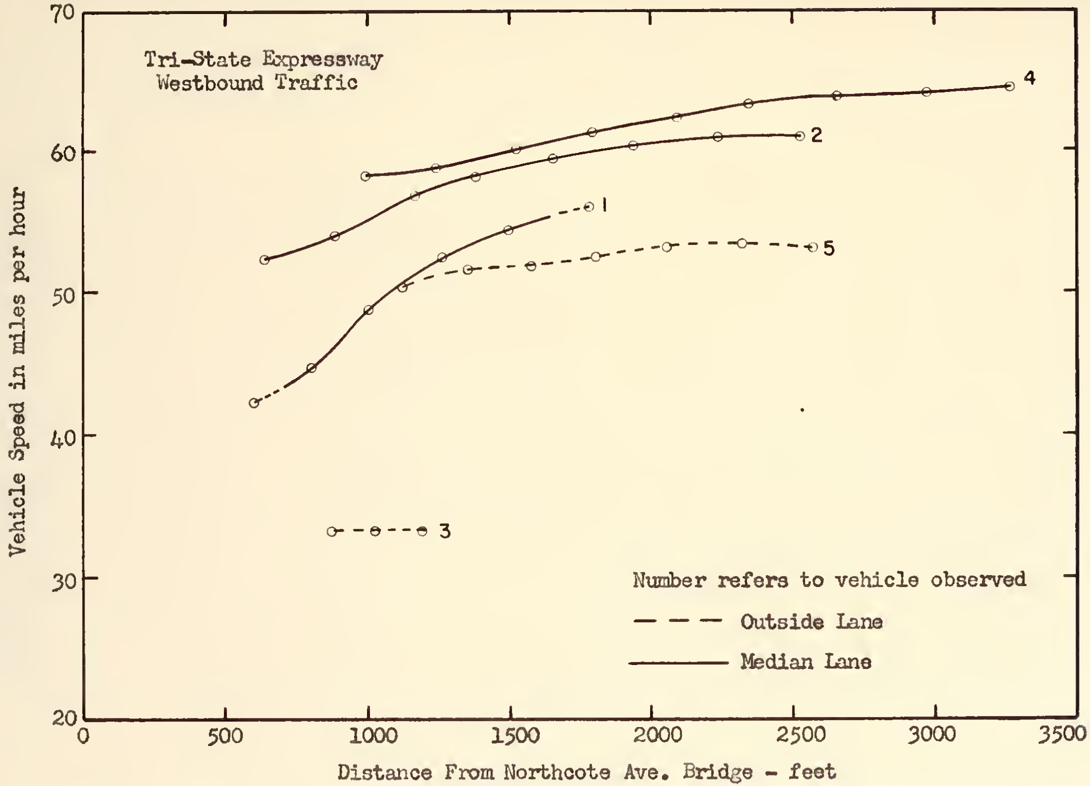

FIGURE 30. VEHICLE ACCELERATION AND SPEED PATTERNS ON A FOUR-LANE FREEWAY AS MEASURED ON AERIAL PHOTOGRAPHS

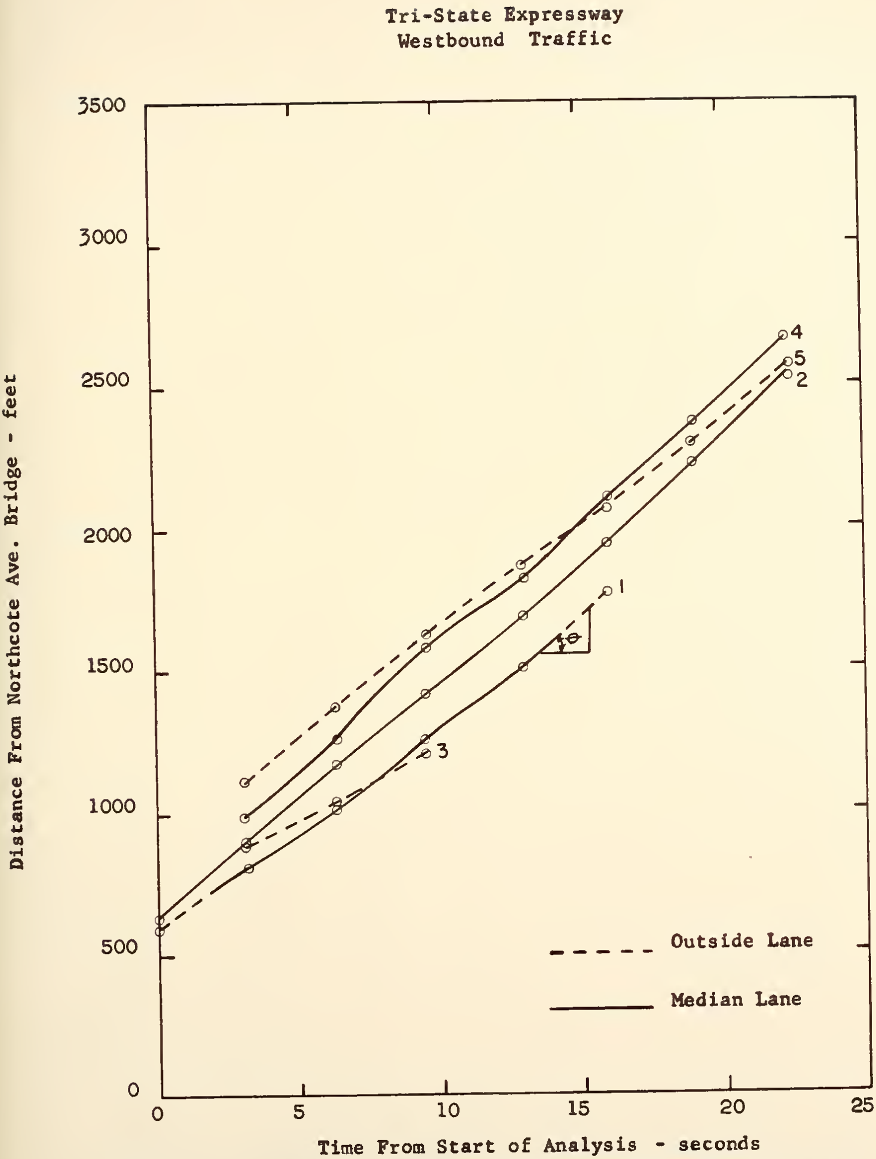

FIGURE 31. TRACKING THE MOVEMENT OF INDIVIDUAL VEHICLES IN TIME AND SPACE BY THE USE OF AERIAL PHOTOGRAPHY

at a concurrent moment in time. Thus, either the vehicles had collided or one was passing the other. For example, reference to Figure 31 shows that vehicle number 1 accelerated from 41 mph to 56 mph in passing vehicle number 3 eight seconds after the start of the photo analysis and 1100 feet west of Northcote Avenue. The passing maneuver of vehicle 1 involved its moving from the outside lane to the median lane and then returning. This was completed in approximately 13 seconds and in somewhat over 950 feet.

Traffic speeds may also be expressed in spacial terms by plotting the mean velocity of the vehicles appearing in each exposure as a function of the aerial photo's location on the route. This was done for the Tri-State Expressway photography and the results are shown in Figure 32. As might be expected on a freeway, little variance in mean speed was observed over the 6480 foot study section. On the other hand, a similar plot for the Shadeland Avenue (State Route 100) site revealed a decided increase in the average speed of vehicles traveling south from the Pleasant Run Parkway intersection. The peak average speed occurred about 1000 feet beyond the Parkway, followed by a reduction in speed as the drivers approached and passed 16th Street (see Figure 33).

A frequently cited rule-of-thumb for safe driving cautions motorists to allow one car length (20 feet) of space between themselves and the preceding vehicle for each 10 mph increment of their speed. Most observers would agree that the rule is frequently violated on today's highways. An analysis of

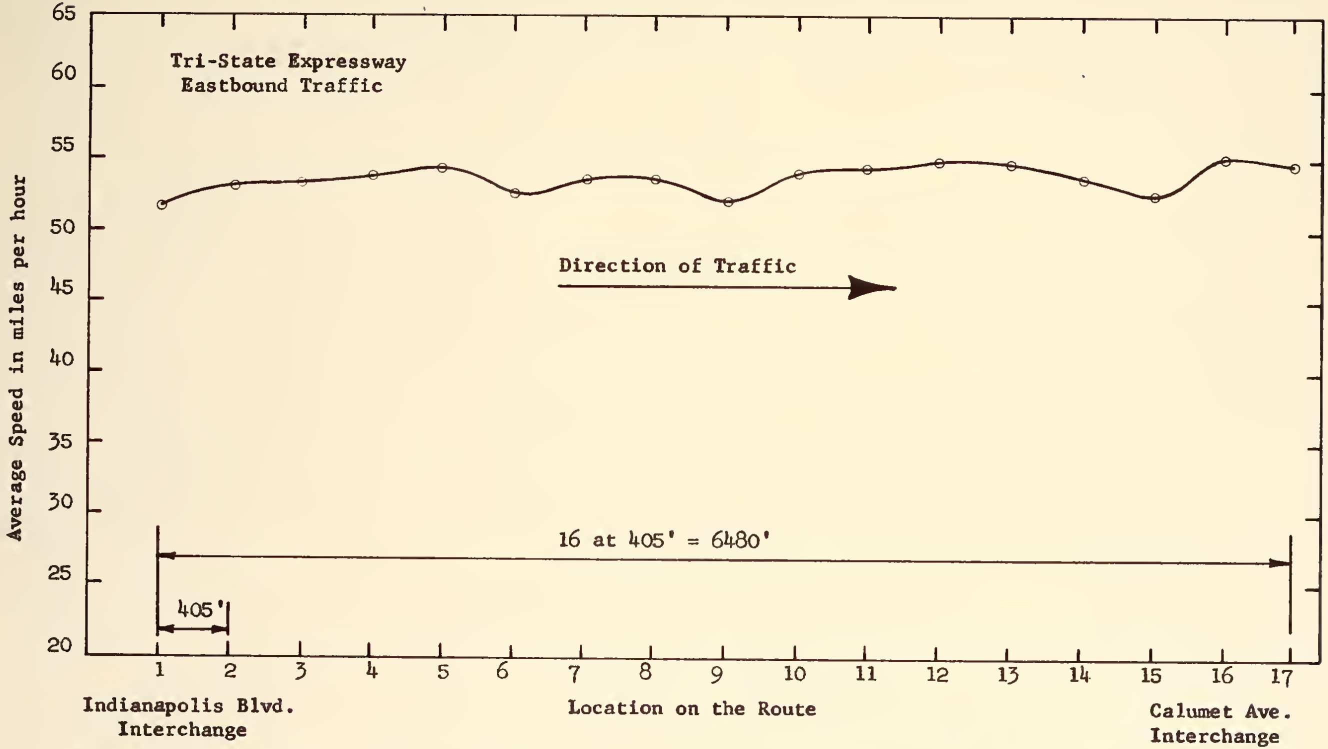

FIGURE 32. AVERAGE VEHICLE SPEED FOR DIRECTIONAL TRAFFIC AS A FUNCTION OF LOCATION ON THE ROUTE AS RECORDED BY AERIAL PHOTOGRAPHY

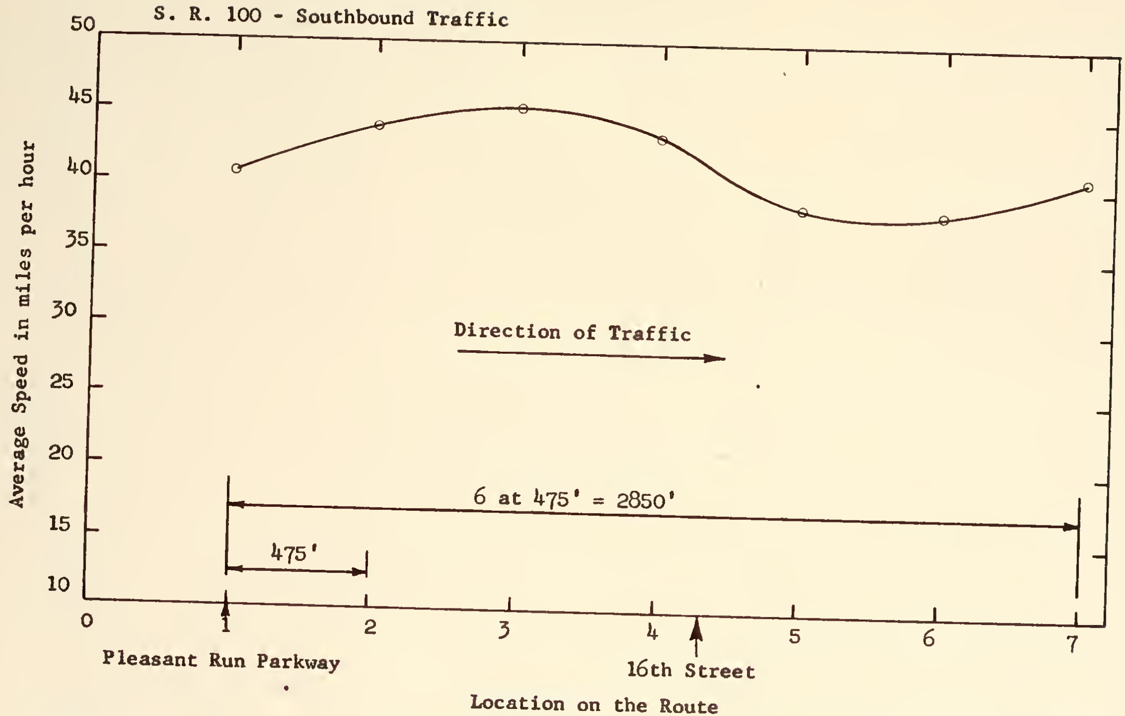

FIGURE 33. AVERAGE VEHICLE SPEED FOR DIRECTIONAL TRAFFIC AS A FUNCTION OF THE LOCATION ON THE ROUTE AS RECORDED BY AERIAL PHOTOGRAPHY

these vehicle spacing patterns assists the investigator in describing the character of traffic density and, as such, represents an important part of any traffic flow study. Since the gap (g) between successive vehicles is a spacial quantity, aerial photography is particularly applicable to this type of survey.

Figure 34 depicts the mean minimum vehicle spacings allowed by passenger car motorists when following vehicles at various speeds. To be sure that the driver of the trailing car was being influenced by the presence of the vehicle ahead, the only cases considered were those in which $g \leq 180$ feet and $(S_L - S_F) \leq \pm 2$ mph. Within a speed range of 30 to 70 mph, simple regression lines were fitted to the data. The outside lane was found to conform reasonably well with the spacing rule, particularly at high speeds. The associated regression equation accounted for 75 percent of the observed variation in spacing. On the basis of this equation, a plot of lane capacity as a function of mean speed was constructed (see Figure 35). As expected capacity dropped off sharply at speeds above 30 mph, with a slowing rate of decline at higher speeds.

The regression line computed for the median lane accounted for 86 percent of the variation in the dependent variable for speeds between 30 and 70 mph (see Figure 34). It is apparent that motorists in the passing lane were willing to tail vehicles at closer range than those in the outside

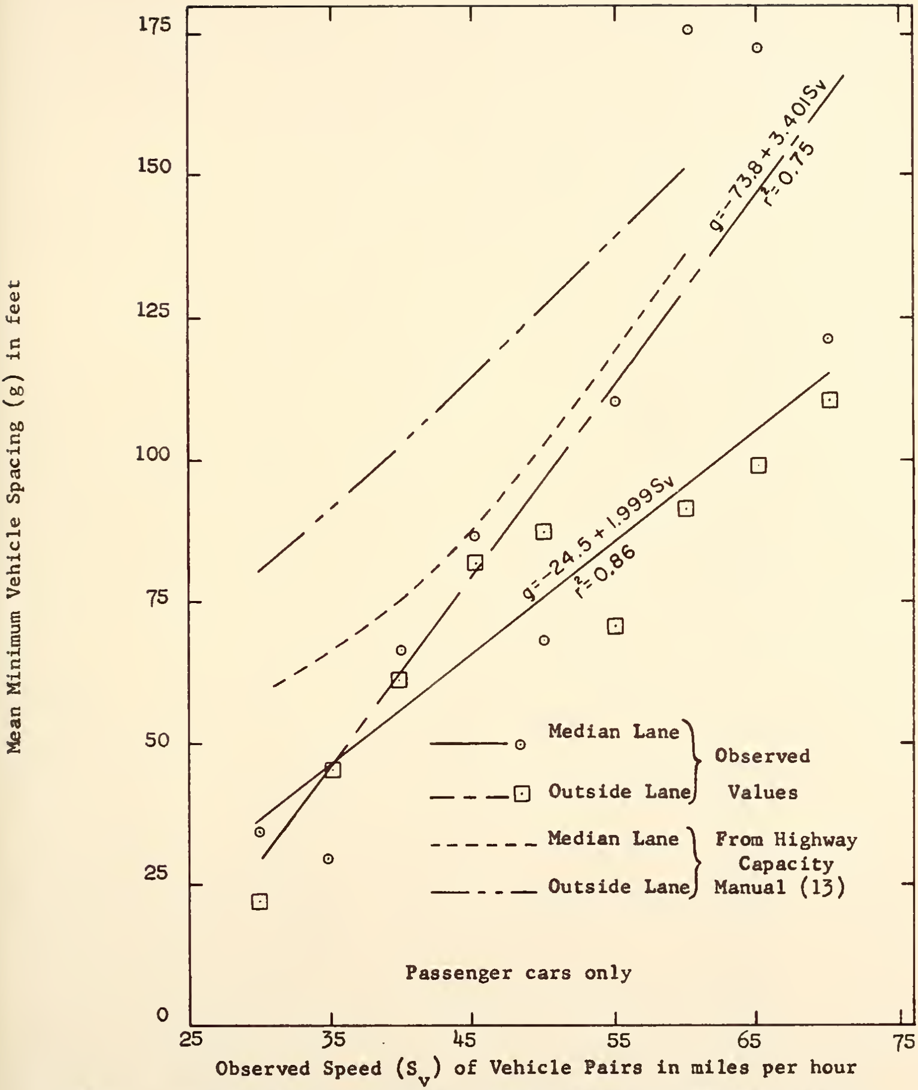

FIGURE 34. MINIMUM SPACINGS ALLOWED BY THE AVERAGE DRIVER WHEN TRAILING ANOTHER VEHICLE AT VARIOUS SPEEDS ON FOUR-LANE DIVIDED HIGHWAYS AS MEASURED ON AERIAL PHOTOGRAPHS

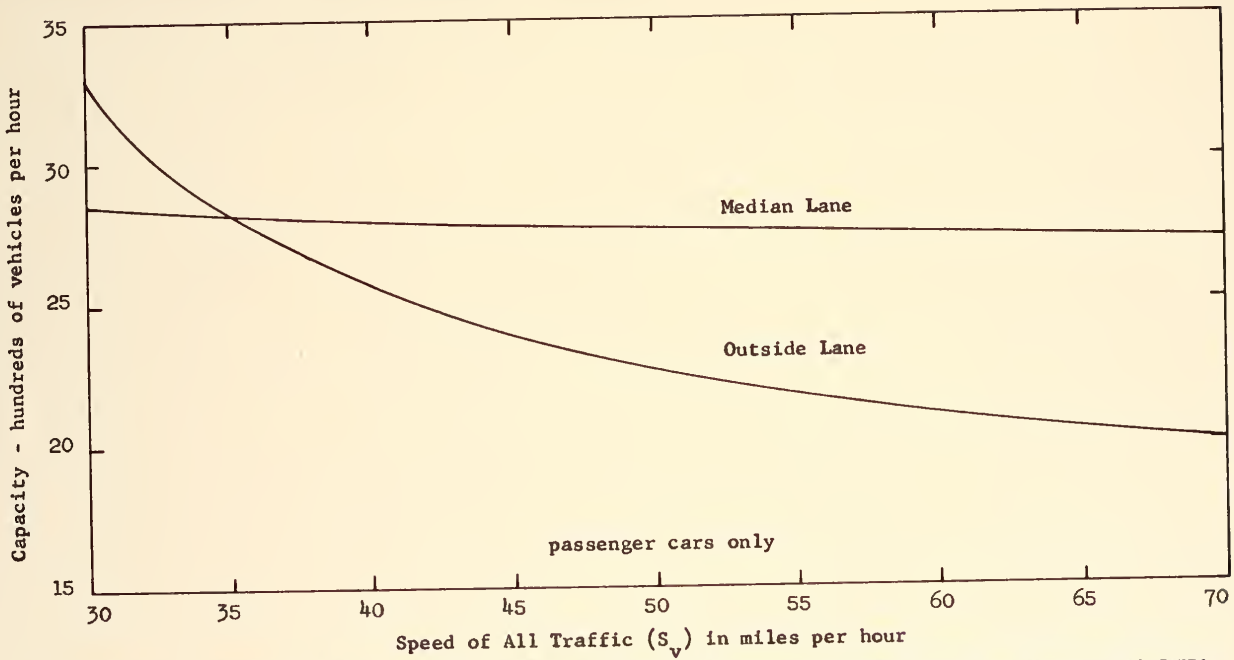

FIGURE 35. MAXIMUM CAPACITY OF EACH LANE OF A FOUR-LANE DIVIDED HIGHWAY BASED ON AVERAGE MINIMUM SPACINGS BETWEEN SUCCESSIVE VEHICLES TRAVELING AT THE SAME SPEED

(right-hand) lane. Plotting capacity versus speed for the median lane's regression equation, one finds virtually no variation in capacity with changes in speed (see Figure 35).

For comparison with the current data, "speed-spacing" curves from the Highway Capacity Manual (13) are included in Figure 34. These curves, based on data collected in the 1940's, would seem to indicate that drivers have become less cautious in recent years.

Figure 36 illustrates the results of a study of lane changing as a function of directional traffic volume on the Tri-State Expressway. The data were obtained from standard aerial photography coverage of the site by noting the number of vehicles changing lanes as a fraction of the total vehicle count for each flight run. A linear regression line was fitted to the data and was found to explain 69 percent of the variation in lane changing practice. The slope of the line tested positive at the 0.1 level of significance and, thereby, afforded the conclusion that an increase in directional volume, within the 950 to 2100 vph range, was accompanied by an increase in the percentage of vehicles changing lanes.

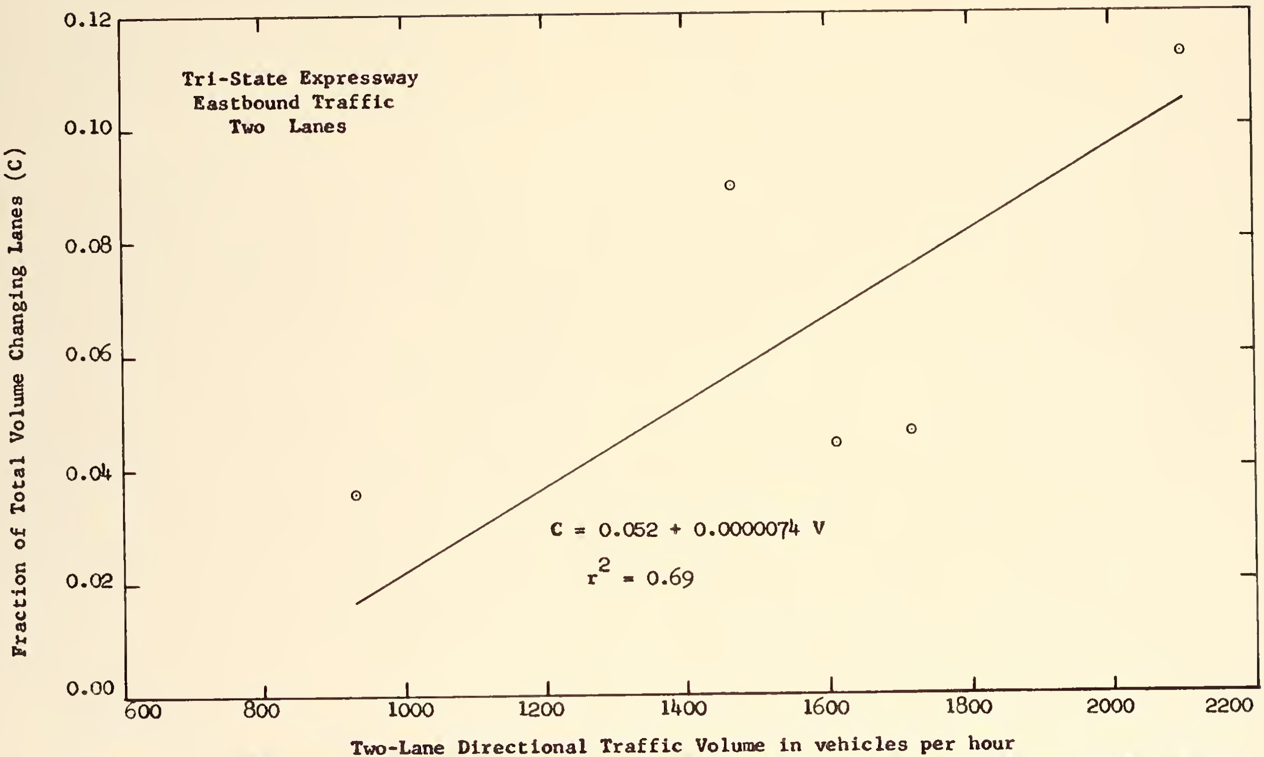

FIGURE 36. LANE CHANGING AS A FUNCTION OF DIRECTIONAL VOLUME ON A FOUR-LANE FREEWAY AS RECORDED BY AERIAL PHOTOGRAPHY

COMPARATIVE ANALYSIS OF THE METHODS

For the purposes of discussion, the comparative analysis of the three traffic survey techniques under study is divided into three general topics:

I. Applicability to the Investigation of Traffic Flow Characteristics.

II. Data Gathering Characteristics.

III. Data Reduction Characteristics.

Costs, time and personnel efficiency, measurement precision and accuracy, and limitations on applicability are among the subtopics detailed for each method.

Applicability to the Investigation of Traffic Flow

Each of the data gathering methods studied proved capable of effectively detecting and recording the basic traffic flow elements of speed, volume and headway. For obtaining a wide variety of additional data, time-lapse aerial photography appears to be the most useful technique. Such physical characteristics as vehicle classification and roadway geometry, condition and environment are readily and permanently recorded by the photographic methods. Since time-lapse aerial exposures afford a "view" of a vehicle's movement over both space and time, the combined physical and

psychological phenomena in traffic flow can be studied in terms of acceleration and deceleration practices; passing behavior; lateral placement; spacing habits; and merging, diverging and weaving patterns. The findings of the present research indicate that aerial photography would be a particularly valuable tool in the investigation of traffic patterns at freeway interchange ramps and large, complex urban intersections. The use of a helicopter, blimp or captive balloon would permit such "limited space" aerial photography.

With color photography facilitating the identification of vehicles and environmental elements, the color intermittent exposures are perhaps even more useful than those in black and white.

Although highly effective in collecting speed, volume and headway information and recording the physical characteristics of the route, Sonne continuous strip aerial photography is limited by its inability to survey individual vehicle and driver behavior over an extended period of time and length of highway. Acceleration, merging, diverging and weaving practices are impossible to detect with continuous strip photography. The principle of the continuous strip method all but prohibits its use for investigating a small area, such as an intersection, for other than very short intervals of time.

The automatic ground method, as represented by the pneumatic tube-graphic recorder system, finds its major limitation in an inability to record traffic patterns over extended

space as well as time. The use of a number of tubes spaced along a highway or throughout an intersection has been attempted (46, 49); however, the method yields a confusing and inadequate "view" of the flow patterns when traffic volumes are high or the intersection complex. Consequently, studies of passing behavior, merging, diverging and weaving patterns; and acceleration and deceleration characteristics cannot be practicably studied by the automatic ground method except in the simplest of situations. In addition, many of the intangible, but pertinent physical and psychological factors associated with the route and its surroundings go unobserved by the machine.

Data Gathering Characteristics

Data gathering, as the term is employed here, encompasses two components of any traffic surveying method: a detecting device and the recording technique. It is toward an analysis of the relative efficiency, accuracy and measurement precision of each method that the following discussion is directed. Although this analysis deals primarily with the collection of speed, volume and headway data, it is applicable to the study of all traffic flow characteristics recorded on the aerial photos.

Equipment, Supplies and Personnel

The previous sections on methodology indicated the equipment,

supplies and personnel employed by each method, and these are summarized, along with estimated costs, in Tables 2, 3, 4 and 5. Comparative cost data are also presented for a typical traffic survey of speeds, volume and headways in Table 6. Where particularly expensive facilities with few general applications are required, costs are based on current equipment leasing or job contracting practices. The reader is cautioned, however, not to place undue significance on any of the cost figures since they merely represent an estimate of current (1962) wages and prices.

These costs can be expected to vary somewhat with the nature and scope of the study. The costs per unit of data gathered would undoubtedly decrease by all methods if the survey period were lengthened. However, the efficiencies of the various methods would probably remain in essentially the same relative order. However, if the scope of the study was expanded to include more sites, important changes in the relative efficiences could be expected. The aerial photography technique can study, with a single complement of equipment and personnel, a large number of sites within close proximity of each other at essentially the same time. On the other hand, one set of equipment and the necessary attending personnel must be assigned to each site when surveying all locations concurrently by automatic ground methods.

Generally speaking, the fixed, ground method entails the least outlay for labor and equipment if the survey is

TABLE 2

EQUIPMENT, SUPPLIES AND PERSONNEL USED IN GATHERING TRAFFIC DATA - BLACK AND WHITE TIME-LAPSE AERIAL PHOTOGRAPHY

Basic Equipment:

- Piper Apache PA-23 aircraft
- K-17C aerial camera
- 12" precision lens
- B-3B intervalometer (2-120 seconds)
- Morse B-5 rewind type film processing unit

Major Supplies:

- Eastman Kodak Super XX Aerographic 1623 black and white film. (or Plus X Aerographic)
- Film processing chemicals
- Photographic paper

Personnel:

- Aircraft pilot
- Photographer
- Film processor
- Photo index compiler

Unit Costs:

Aircraft (with camera system and pilot)	-	$ 30.00/hour*
Photographer	-	$ 3.00/hour*
Film (150' roll)	-	$ 57.75/roll*
@175 exposures	-	$ 0.33/exposure*
Film processing(labor, chemicals,etc.)		
heavyweight 9" x 9" prints	-	$ 0.26/print*
lightweight 9" x 9" prints	-	$ 0.23/print*
Compilation of index sheet		
(approx. 50 prints)	-	$ 5.00/sheet** .10/print

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* Costs estimated by the Indiana State Highway Commission, Bureau of Photogrammetric and Electronic Processes, 1962.

** Does not include cost of the 9" x 9" prints making up the index.

TABLE 3

EQUIPMENT, SUPPLIES AND PERSONNEL USED
IN GATHERING TRAFFIC DATA - COLOR
TIME-LAPSE AERIAL PHOTOGRAPHY (TRANSPARENCIES)

Basic Equipment:

Piper Apache PA-23 aircraft
K-17C aerial camera
12" precision lens
B-3B intervalometer (2-120 seconds)
Morse B-5 rewind type film processing unit
with seven 6 gallon tanks and reel

Major Supplies:

Eastman Kodak Aero-Ektachrome color film
Color film processing chemicals and supplies

Personnel:

Aircraft pilot
Photographer
Film processor

Unit Costs:

Aircraft (with camera system and pilot)	- $30.00/hour*
Photographer	- $ 3.00/hour*
Film (40' roll)	- $72.00/roll*
@ 45 exposures	- $ 1.60/exposure*
Film processing for transparencies	- $46.90/roll*
@ 45 exposures	- $ 1.04/exposure*

* Costs estimated by the Indiana State Highway Commission, Bureau of Photogrammetric and Electronic Processes, 1962.

TABLE 4

EQUIPMENT, SUPPLIES AND PERSONNEL USED

IN GATHERING TRAFFIC DATA - SONNE

CONTINUOUS STRIP AERIAL PHOTOGRAPHY

Basic Equipment:

Aircraft
Sonne continuous strip camera (e.g. KA-18A) with automatic synchronization system and gyrostabilization mount
Film processing unit

Major Supplies:

Aerographic film
Film processing chemicals
Photographic paper for strip print

Personnel:

Aircraft crew
Film processors

Unit Costs:

Aircraft	- $60.00/hour*
Flight crew labor	- $192.00/day*
@ 8 hours/day	- $24.00/hour
(Flight crew per diem = $30.00)	
Film processing	- $350.00/500'roll*

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* Costs estimated by Chicago Aerial Survey, Franklin Park, Illinois, 1962.

TABLE 5

EQUIPMENT, SUPPLIES AND PERSONNEL USED IN GATHERING TRAFFIC DATA - AUTOMATIC RECORDER METHOD

Basic Equipment:

Flexible pneumatic tubes
Esterline Angus Model A.W. twenty pen graphic recorder
12-volt storage battery to power the recorder

Major Supplies:

Recorder ink
Recorder tapes (charts)

Personnel:

Recorder attendant for each site

Unit Costs:

Equipment	- $1.00/hour(approx. rental)
Data tapes (100')	- $2.00/tape*
@ 100'/tape	- $0.02/foot of tape
@ 12" movement/minute	- $1.20/hour
Personnel	- $3.00/hour

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* Cost estimate based on 1961 Price List of the Esterline Angus Instrument Company, Indianapolis, Indiana.

TABLE 6

COMPARISON OF BASIC COSTS OF GATHERING DATA BY EACH METHOD FOR A TYPICAL TRAFFIC STUDY

Study Site: Four-lane divided highway

Data Sought: Speeds and headways for 10,000 vehicles. Classification of vehicles by type. Traffic volumes during the period of speed-headway data collection.

Assumptions:
1. Route volume is approximately 5000 vehicles per hour.
2. The methodology is the same as described earlier in this report.
3. Two-mile study section of highway.
4. Sixteen flight passes over the study section per hour (Eight in each direction).
5. Twenty five exposures per flight pass.
6. Average of 180 vehicles recorded per flight pass.
7. Pen recorder set-up and dismantling time totals one hour.

Costs*:

A. Black and White Time-Lapse Photography

1390 exposures required.
400 exposures taken per hour.
3.48 hours of flight time required at the site.

Aircraft and Crew	@ $33.00/hour -	$ 115.00
Film	@ $0.33/exposure -	$ 459.00
Film Processing-prints and indexes	@ $0.59/exposure -	$ 820.00
Total Cost of photo coverage =		$1394.00
	or	$0.14/vehicle

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* Excluding administrative and planning costs and travel expenses to and from the site. These quantities are assumed to be approximately equal for all methods.

TABLE 6 (continued)

B. Color Time-Lapse Photography

1390 exposures required.
400 exposures taken per hour.
3.48 hours of flight time required at the site.

Aircraft and Crew @ $33.00/hour	-	$ 115.00
Film @ $1.62/exposure	-	$2253.00
Film processing @ $1.04/exposure	-	$1446.00
Total Cost of photo coverage	=	$3814.00
	or	$ 0.38/vehicle

C. Sonne Continuous Strip Photography

326 feet of film required
3.48 hours of flight time required at the site.

Aircraft and Crew @ $84.00/hour	-	$ 292.00
Film and processing @ $350.00/ 500' roll	-	$ 228.00
Total Cost of photo coverage	=	$ 520.00
	or	$ 0.05/vehicle

D. Automatic Ground Recorder Method

2 hours of data collection required
1 hour required for setting up and dismantling equipment

Equipment (at each site) @ $1.00/hour	-	$ 3.00
Data tapes @ $1.20/hour	-	$ 2.40
Personnel (at each site) @ $3.00/hour	-	$ 9.00
Total Cost of data gathering	=	$14.40
	or	$0.0014/ vehicle

limited to concurrent data collection at a few local sites. Standard time-lapse aerial photography becomes practical when the study encompasses many locations within a few minutes flying time of each other. Color photography remains significantly more expensive than the standard black and white aerial photos; whereas, for a typical traffic study, the cost of Sonne continuous strip coverage lies between the rates associated with time-lapse exposures and the mechanical ground technique (see Table 6).

If the expansion of a ground survey's scope to include the gathering of new information involves additional labor and mechanical or electronic devices, the aerial photographic techniques, being capable of collecting virtually all pertinent data simultaneously, would undoubtedly increase in relative efficiency.

Data collection on aerial photographs is probably less time consuming than the pneumatic tube-graphic recorder system described by Sonntag if delays attributable to bad weather are discounted. Since the moving aircraft "seeks out" vehicles at a rate faster than they would normally pass a fixed point, recording data for a specified sample size can be accomplished more rapidly through aerial photography than by conventional ground devices. This time advantage becomes increasingly pronounced as the study's scope is broadened.

Precision of Recorded Data

The intermittent aerial photography technique described afforded precisions of ± 0.6 feet for travel distances, ± 0.3 feet for distance headways and approximately ± 0.1 seconds for the photo interval. The Sonne continuous strip photos of 1:1800 scale ratio are able to support data precisions of about ± 0.3 feet, ± 0.3 feet and ± 4 miles per hour for travel distances, headways and plane speeds respectively.*

The maximum precisions yielded by the Esterline Angus recorder tapes for travel time and arrival time quantities were ± 0.05 seconds and ± 0.025 seconds respectively.

Improvements in these levels of precision could be achieved for each technique through modifications in the methodology. For example, an increase in the photo scale would permit more precise linear measurements. Similarly, a faster movement of the pen recorder chart would yield a time precision greater than that possible from the 12-inch per minute rate used by Sonntag. However, in both instances, the increased precision is secured at the expense of the method's efficiency. For meeting the requirements of a normal traffic study, the levels of precision associated with the data collection procedures of this research are considered adequate.

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* Based on conversations with John H. Wolvin, General Manager, Chicago Aerial Survey, Franklin Park, Illinois, 1962.

Accuracy of Data Gathering Methods

The design of the present research did not permit a detailed analysis of each method's accuracy in gathering speed, volume, headway, vehicle type and lane use data. However, certain pertinent generalizations can be made which indicate that all the methods, when properly executed, afford the ± 10% accuracy required of most traffic surveys.

Standard Aerial Photography. Knowledge of the true interval between successive photographs and a precise determination of the scale of photography are fundamental to an accurate measurement of speeds, volumes and headways from intermittent photographs. In the present study, the interval between exposures was approximately three seconds, with a maximum variance over a given flight run of ± 0.05 seconds or less than ± 2 percent.

The scale of photography is most accurately determined by frequent reference to ground control points. Concrete pavement joints, sign posts and other ground-level landmarks along the route serve as reliable and easily obtained points of control. Since route elevation may vary as well as flight altitude, only by repeated checks of scale along the length of the study section can accuracy be maintained. In the present studies of level highway sections, the employed scale of approximately 1:1800, once precisely defined, was found to vary less than ± 5 percent over a one to two-mile flight run or across an individual photograph.

The normal pitch and roll effects associated with standard aerial photography are not significant sources of error in scale determinations provided the pilot is experienced in aerial mapping and has made a conscientious effort to minimize motion about these axes. It seems probable, however, that atmospheric conditions during the flight would have a profound effect on scale variations related to pitch, roll and changes in flight attitude.

Some difficulty in maintaining a constant aircraft ground speed was experienced in the current research. It will be noted, however, that none of the traffic flow characteristics investigated require a knowledge of plane speed on a photo-by-photo basis. The easily and accurately obtained average ground speed of the aircraft over an entire flight run is adequate for finding route volume by the "Speed Ratio" relationship (see equation 4). The accuracy of the resulting volume is limited by the combined effects of any photo interval or scale errors.

Obstruction of the vertical view and shadows on the travel lanes are sources of error which vary in magnitude from site to site. These factors naturally influence the selection of locations to be surveyed by aerial methods and the periods during the day when a photographic study can be conducted.

Sonne Continuous Strip Aerial Photography. The accuracy of data derived from continuous strip photography is a function

of the camera system's ability to synchronize the film velocity with the ground image movement and the accuracy of the measured ground speed of the aircraft. Photo scale may best be determined by repeated reference to ground control points along the route. Normal aircraft roll and pitch are not significant factors in strip photo traffic studies as long as a flight elevation of 1000 feet is not exceeded and the flight path is held tangent*. As with all photographic techniques, shadows and obstructions of the view represent particularly troublesome sources of error.

Under normal conditions, it is estimated that vehicle speeds from strip photos are accurate to ± 5 percent while volumes are generally within ± 10 percent and distance headways within ± 5 percent of true values.

<u>Automatic Ground Method</u>. For most applications, the graphic pen recorder can be expected to yield speeds, volumes and headways to within ± 10 percent of the actual values.

Errors attributable to variations in rate of tape movement are negligible if the spring drive mechanism is kept wound or an external electric motor used. Failure of the pneumatic tubes to detect some vehicle crossings can be troublesome when vehicles of widely varying weight travel the route since

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* Correspondence with John H. Wolvin, General Manager, Chicago Aerial Survey, Franklin Park, Illinois, December 6, 1961.

tubes adjusted for the heaviest trucks frequently do not detect the passage of light cars. In addition, vehicles in the midst of a passing maneuver or those riding slightly off the travel lanes may evade detection unless care is taken in laying the tubes and analyzing the data. On the other hand, vehicles which stop on, or back across, the tubes will also distort the record of traffic flow.

Classification of vehicles by type is, at best, crudely accomplished by axle counts. Segregation of "passenger cars" into passenger vehicles and light trucks or "trucks" into light, medium and heavy trucks, buses, house trailers, etc. is virtually impossible by the use of detector tubes.

However, it is the psychological effect which the presence of the tubes has on the average driver that introduces perhaps the most significant distortions to normal traffic patterns. Field observations indicated that ground methods utilizing pneumatic tubes on the roadway probably yield slightly slower speeds and shorter distance headways than are representative of the route's traffic.

Operational Problems and Limitations

During the course of the research, the major operational problems and limitations associated with data gathering by each method were noted. Some of these have been discussed in the preceding sections while others are detailed below.

Standard Aerial Photography. Hampering the effectiveness of the time-lapse aerial photography technique were delays due to inclement weather, its restriction to daylight hours, obstructions to the aerial view, the necessity of maintaining a tangent flight path, and a fluctuating photo scale caused by changes in topography and/or flight elevation. In addition, variations in plane speed occasionally resulted in insufficient exposure overlap.

Probably the method's most serious drawback is its dependence upon the weather. Not only does bad weather delay the securing of aerial coverage, but anything less than ideal atmospheric conditions will have a detrimental effect on the scale of the photography flown. The magnitude of variations in flight altitude and speed, severity of roll and pitch, and extent of drift from the designated flight line are all functions of atmospheric conditions as well as pilot competence.

Standard black and white aerial photography is limited to the daylight hours. The restrictions on color photography are even more severe since its quality suffers noticeably when taken within two hours of sunrise or sunset. Although the technique was not explored in this study, the use of infra-red film might permit photo surveys during periods of darkness or haze.

Obstructions to the vertical view pose a serious problem when surveying traffic from the air. Not only may vehicles

be hidden by trees overhanging or bridges crossing the travel lanes, but they may also be obscured by cloud, smoke or haze cover; other aircraft; or tall roadside buildings.

Even in reasonably calm air, considerable variance in aircraft ground speed often occurs and may actually be aggravated by the pilot's repeated attempts to correct each slight deviation from the desired velocity. The result is a variability in exposure overlap, the critical factor in assuring each vehicle's appearance in two succesive photos.

Intolerable scale distortions due to banking of the aircraft are introduced if an attempt is made to follow a curvilinear section of highway. Slight or reverse curvatures may be successfully photographed from a tangent flight line provided a sufficiently small scale is employed (see Figure 37a). However, most highway curves can be adequately covered only by flying a succession of tangents to the section (see Figure 37b).

Pronounced changes in ground elevation over the length of highway being surveyed will result in significant variations in the scale of photography. If the investigator is to be cognizant of these scale changes, there must be adequate and accurate ground control throughout the study area.

Sonne Continuous Strip Aerial Photography. The problems associated with collecting traffic data by continuous strip aerial techniques are essentially the same as those of time-lapse photography, save the difficulties related to maintaining

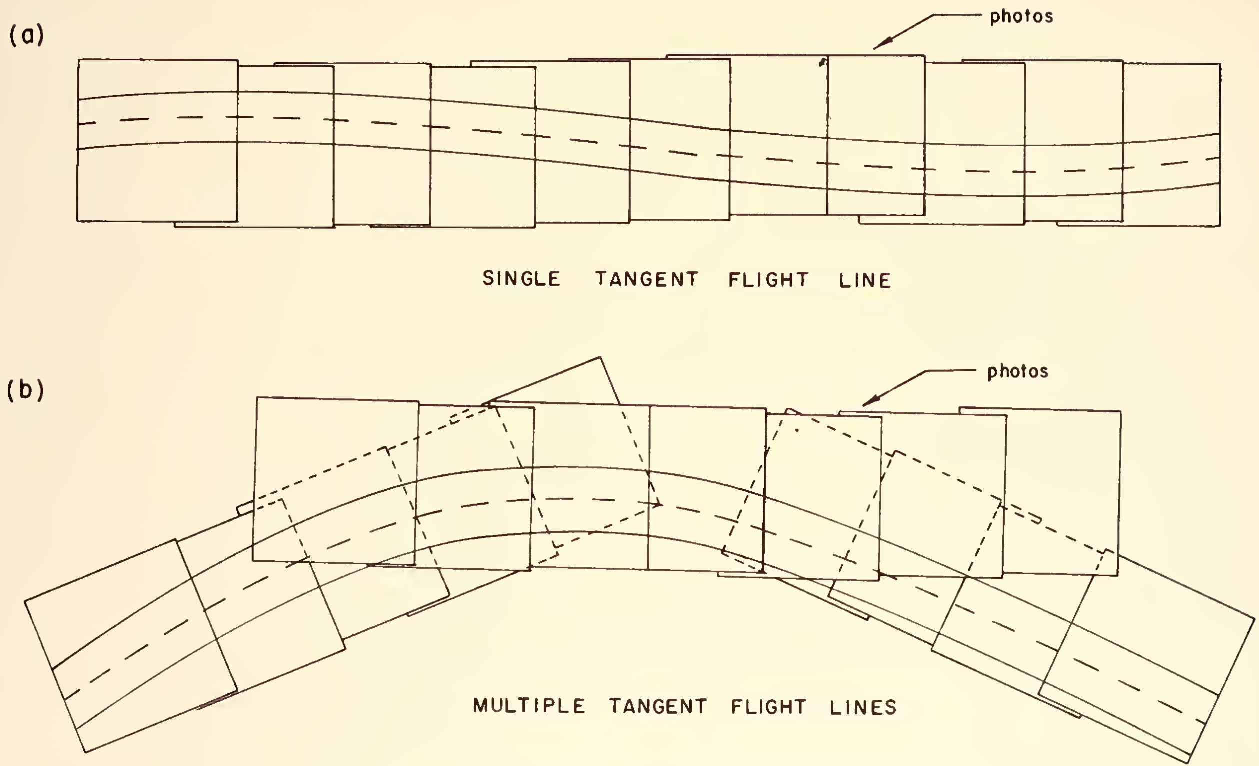

FIGURE 37. AIRPHOTO COVERAGE OF HIGHWAY CURVATURES

sufficient overlap. Of particular importance is the necessity of accurately determining and maintaining the ground speed of the aircraft and synchronizing the image motion to the film speed.

Automatic Ground Method. Among the problems plaguing the pneumatic tube-graphic recorder method are vandalism, a difficulty in camouflaging the equipment, loosening of the tubes, slow downs in chart movement as the drive mechanism unwinds, the time consuming task of setting up and monitoring the equipment, and an occasional failure to detect light vehicles. In addition, the drive mechanism's susceptibility to freezing puts limitations on the use of these machines in extremely cold climates. Likewise snow and ice on the roadway's surface can prohibit the use of detector tubes.

Data Reduction Characteristics

The reduction and tabulation of data is usually the most time consuming and costly phase of a traffic study. Thus, it is appropriate that this report should devote considerable attention to a comparative analysis of the economics, precision, time efficiency, and accuracy of the data reduction techniques for the various information gathering methods investigated. For discussion purposes, the analysis is limited to the reduction of speed, volume and headway quantities.

Equipment and Supplies

In designing the data reduction procedures employed in this study, every effort was made to minimize the amount of special equipment and skilled labor required.* Therefore, the methods described can be readily adopted by any highway organization with the hiring of an adequate clerical staff.

The equipment requirements of each method were indicated in the earlier discussion on reduction procedures and are summarized, along with estimated costs per man, in Table 7. The graphical tape technique is the most economical to equip. Using tools common to most engineering offices, each man can be outfitted for about $5.80. The addition of grease pencils, appropriate engineers' scales, and a magnifying glass renders the black and white intermittent aerial photography prints only slightly more expensive ($13.10 per man) to equip for data reduction than the pen recorder tapes. If a lens stereoscope is used an additional assessment of $5.00 per man would be required. The necessity of a light table for viewing the transparencies increases the cost to $23.10 per man when obtaining data from color exposures. The estimate of $50.20 per operator for the Sonne stereo viewing technique is by far the highest of these costs.

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* An exception to this would be the optional use of Sonne stereo viewers in analyzing the continuous strip photography.

TABLE 7

EQUIPMENT USED IN REDUCING TRAFFIC DATA

A. Black and White Time-Lapse Aerial Photographs:

Precision engineers' scale (100 units/inch)	-	$ 4.80
Pocket magnifying lens (3x)	-	2.00
Reading glass	-	4.90
Grease pencil	-	.20
Drafting triangle (12")	-	1.20
Total	=	$13.10/man

B. Color Time-Lapse Aerial Photographs:

Precision engineers' scale (100 units/inch)	-	$ 4.80
Pocket magnifying lens (3x)	-	2.00
Reading glass	-	4.90
Grease pencil	-	.20
Light table (32" x 31")	-	10.00(1 month rental)
Drafting triangle (12")	-	1.20
Total	=	$23.10/man

C. Sonne Continuous Strip Aerial Photographs (Stereo Method):*

Stereo Viewer and Stereo Comparator	-	$50.00(1 month rental)
Grease pencil	-	.20
Total	=	$50.20/man

D. Pen Recorder Tapes:

Precision engineers' scale (50 units/inch)	-	$ 4.60
Drafting triangle (12")	-	1.20
Total	=	$ 5.80/man

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* Strip photography may be analyzed non-stereoscopically with the same equipment used with black and white time-lapse photography.

Precision of Measurements

The precision of the data reduction technique associated with each of the various methods was determined in light of the requirements common in traffic analysis and the capabilities of the equipment employed.

Standard Aerial Photography. When reading a 100 parts to the inch engineers' scale to $\pm$ 0.025 inches, distances on photography of 1:1800 scale ratio were determined to within $\pm$ 0.4 feet. The time interval between exposures was found to vary up to $\pm$ 0.05 seconds when the photos were taken approximately three seconds apart. Thus, considering the two measurements required for establishing speed and assuming vehicle velocities of 30 miles per hour or greater, a reduction precision of at least $\pm$ 1 foot per second or $\pm$ 0.7 miles per hour could be maintained for speed data.

The precision of a volume count from airphotos* is a function of the time duration of the flight as well as systematic errors involved in determining vehicle and plane speeds. It is estimated that the calculated directional volumes were good to within $\pm$ 10 percent, with the precision improving with increasing flows.

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* "Speed Ratio" method for calculating traffic volumes from aerial photography.

<u>Sonne Continuous Strip Airphotos</u>*. When using a Sonne stereo viewing — measuring device, normal speed data can be reduced from 1:1800 scale strip photography to within ± 1 mile per hour. Linear measurements, such as headways, are precise to ± 0.1 foot and a calculated directional volume of 1000 vehicles per hour is estimated to be true within ± 10 percent for normal traffic speeds.

<u>Automatic Ground Method</u>. Reading from a 50 unit per inch engineers' scale, the Esterline Angus graphic tape yielded time measurements to ± 0.025 seconds. With the 100 foot distance between tubes established to within ± 0.2 feet, a speed precision of at least ± 3 feet per second or ± 2.5 miles per hour was attainable. The precision was substantially improved at the lower speeds. In securing arrival times, a reduction precision of ± 0.05 seconds was considered adequate. No inherent measurement error was associated with the volume count.

Man-Hour Requirements

A complete record was maintained of the man-hour requirements for reducing the speed, volume and headway data from the recorder tapes and aerial photographs. A two-way classification, mixed model analysis of variance (ANOV) statistical design was

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* Data based on information supplied by Chicago Aerial Survey, Franklin Park, Illinois, 1962.

employed for comparing the efficiencies of each method*. Tests were made, at a 0.05 level of significance, of the following hypotheses:

1** $\mu_C = \frac{\mu_A + \mu_B}{2}$

2** $\mu_A = \mu_B$

where

μ_A = true mean rate of data reduction from standard black and white aerial photographs

μ_B = true mean rate of data reduction from the color aerial photographs

μ_C = true mean rate of data reduction for the graphic recorder ground method

3. $\mu_1 = \mu_2 = \mu_3 = \mu_4$

where

μ_i = true mean data reduction rate for the ith worker. The four workers (J, R, H and D) represent a random sample for all possible workers.

4. There is no interaction between "Methods" and "Workers".

The test procedure was applied to speed, volume and headway data reduction rates considered independently as well as their combined efficiency and is outlined below and in

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* The information supplied by Chicago Aerial Survey on the efficiency of data reduction from Sonne strip photography was not of a form to permit its inclusion in the statistical tests.

** Hypotheses 1 and 2 represent mutually orthogonal contrasts for the "Methods".

Tables 8, 9, 10 and 11. Three methods were analyzed: standard black and white aerial photographs, color aerial photography, and the detector tube-graphic recorder system. The same four workers (J, R, H and D) were assigned to each method and task and three* reduction rate observations were noted for each method-worker cell.

After three to five hours of training and practice, the workers were considered to be proficient at obtaining data from the photographs. A one-hour training period was found sufficient for working with the pen recorder tapes. Each man was supplied with a time sheet (see Figure 38) and instructed to work at a natural pace, recording hourly the amount of data reduced. When only a fraction of an hour was devoted to a task, this fact was noted and, where necessary, the rate of reduction was expanded to an hourly basis. Such an expansion was considered valid since an individual's efficiency at obtaining any of the required data was not found to vary over an hour's work.

The various tasks were grouped into five categories:

I. Numbering the vehicles on the tapes or photos.

II. Classification of vehicles by lane and type.

III. Obtaining vehicle speed as a function of either the time required to travel a fixed distance (graphic tapes) or the distance traveled per unit time (aerial photographs).

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* The sample size was largely governed by practical limitations on the research. However, three observations per cell in each of the twelve cells was found sufficient to yield a desirable 24 degrees of freedom in the ANOV "error" term and a satisfactory 6 degrees of freedom for the method-worker interaction (MW).

Name M. Cassiday

Site	Type of Work	Hours Spent	Vehicles Reduced	Date
Tri	headway meas.	1	35	9/28
Tri	headway meas.	1/2	8	9/28
100	travel distance meas.	1/2	14	10/2
100	headway meas.	3/4	15	10/3
31	numbering vehicles	1/4	37	10/19
31	travel distance meas.	1	35	10/19
Arl	speed from tapes	1	100	10/24
Arl	arrival time from tapes	1	174	10/24

FIGURE 38. WORKER EFFICIENCY SHEET

IV. Measuring arrival times (tapes) or distance headways (aerial photographs).

IVa. Conversion of arrival times into time headways.

V. Obtaining traffic volumes in terms of vehicles per minute.

The ANOV model used was:

$$Y_{ijk} = \mu + M_i + W_j + (MW)_{ij} + E_{ijk}$$

where

μ = true mean reduction rate

M_i = deviation from μ of the ith method's true mean reduction rate.

W_j = deviation from μ of the jth worker's true mean rate of reduction.

$(MW)_{ij}$ = interaction of methods and workers

and

E_{ijk} = deviation from μ of the kth observation for the jth worker on the ith method.

For this analysis, the following assumptions were made:

a. μ is a fixed, unknown parameter.

b. M_i is fixed; that is, the tests are generalized only to the methods A, B and C. By definition, $\sum M_i = 0$.

c. W_j is a random variable; that is, the results are generalized to all workers of which there is a random sample: W_j NID $(0, \sigma_w^2)$*.

d. $(MW)_{ij}$ is a random variable: $(MW)_{ij}$ NID $(0, \sigma_{MW}^2)$.

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* NID $(0, \sigma_w^2)$ = normally and independently distributed about a mean of zero with a variance of σ_w^2.

e. There is a normal distribution of errors:

E_{ijk} NID $(0, \sigma^2)$.

With the assumptions of homogenity of variance and a normal population, the standard F test could be used for testing the hypotheses of interest. Summaries of the analysis of variance for each of the basic traffic measurements are outlined in Tables 8 thru 11.

Tasks I, II and III were combined and a single "speed" reduction rate computed in minutes per vehicle. At a 0.05 level of probability, the time-lapse aerial photography methods (A and B) were not found to differ significantly in their efficiency of speed data reduction (Table 8). The difference between the rates associated with the automatic method and the photographic technique was significant, with the former being considerably more efficient. The mean rates for the black and white photos, color exposures and recorder tapes were 2.73, 2.74 and 0.62 minutes per vehicle respectively. Differences among workers were significant, but the interaction of workers and methods was not significant.

Table 9 summarizes the ANOV for the efficiency of the headway measuring tasks (IV and IVa). When tested at a 0.05 level, the color and black and white aerial photography differed significantly, with the black and white prints being the more rapidly reduced. In addition, the graphic tapes tested more efficient than the photographic method. Although differences among workers were significant, the method-worker

TABLE 8

SUMMARY OF ANALYSIS OF VARIANCE FOR SPEED

DATA REDUCTION TIME

Reduction Time (Minues per Vehicle)

Methods \ Workers	J	R	H	D
A B. and W. Airphotos	4.4 2.9 3.1	3.3 2.8 2.2	3.2 2.1 2.3	2.1 1.9 2.6
B Color Airphotos	3.4 2.7 2.7	2.5 2.2 2.2	3.1 2.6 2.8	2.8 3.0 2.9
C Recorder Tapes	0.8 0.7 0.7	0.6 0.5 0.5	0.5 0.6 0.5	0.7 0.6 0.7

ANOV Table

Source	d.f.	Sum of Squares	Mean Squares	Variance Ratio	$F_{(0.05)}$	Concl.
Workers (W)	3	1.492	0.497	3.404	3.01	S
Methods (M)	2	35.984	17.992			
C_1	1	0.0004	0.0004	0.001	5.99	NS
C_2	1	35.984	35.984	103.134	5.99	S
W x M	6	2.094	0.349	2.388	2.51	NS
Error	24	3.507	0.146			
Total	35	43.076				

C_1 = between Methods A and B

C_2 = between the mean of Methods A and B and Method C

NS = non-significant variance

S = significant variance

TABLE 9

SUMMARY OF ANALYSIS OF VARIANCE FOR

HEADWAY DATA REDUCTION TIME

Reduction Time (Minutes per Headway)

Workers / Methods	J	R	H	D
A B. and W. Airphotos	1.1 1.7 1.1	1.2 1.0 0.8	1.2 1.1 0.9	1.0 0.7 0.8
B Color Airphotos	1.6 1.5 1.8	1.5 1.0 1.0	1.3 0.9 1.1	1.4 1.5 1.0
C Recorder Tapes	0.7 0.7 0.6	0.7 0.6 0.6	0.6 0.5 0.4	0.5 0.4 0.4

ANOV Table

Source	d.f.	Sum of Squares	Mean Squares	Variance Ratio	$F_{(0.05)}$	Concl.
Workers (W)	3	0.665	0.222	6.003	3.01	S
Methods (M)	2	3.417	1.709			
C_1	1	0.375	0.375	7.834	5.99	S
C_2	1	3.042	3.042	63.552	5.99	S
W x M	6	0.287	0.048	1.296	2.51	NS
Error	24	0.887	0.037			
Total	35	5.256	0.150			

C_1 = between Methods A and B

C_2 = between the mean of Methods A and B and Method C

NS = non-significant variance

S = significant variance

interaction was not. The respective reduction rates for methods A, B and C were 1.05, 1.30 and 0.56 minutes per headway.

Variances in the rates of minute volume determinations were analyzed and a summary is presented in Table 10. Once again, the automatic recorder tapes afforded significantly faster data reduction than the photographs. The aerial photo methods (A and B) did not test significantly different. Average rates of reduction were 0.53, 0.53 and 0.02 minutes per vehicle for the black and white prints, color transparencies, and graphic tapes respectively. The differences among workers tested significant at the 0.05 level, as did the method-worker interaction.

Converting all the reduction rates into minutes per vehicle, Table·11 depicts the ANOV for the combined tasks. At a 0.05 level of probability, differences between the aerial photography methods and the method-worker interaction tested not significant. The data tapes, on the other hand, remained significantly more efficient than the photogrammetric technique. The mean rates of reduction for black and white prints and color photos were 4.33 and 4.57 minutes per vehicle as contrasted with 1.17 minutes for the recorder tapes. Mr. John Wolvin, Manager, Chicago Aerial Survey, estimates that 3 minutes per vehicle is required for the reduction of speed, volume and spacing data from continuous strip photography.

TABLE 10

SUMMARY OF ANALYSIS OF VARIANCE FOR

VOLUME DATA REDUCTION TIME

Reduction Time (Minutes per Vehicle)

Workers / Methods	J	R	H	D
A B. and W. Airphotos	0.39 0.56 0.48	0.38 0.48 0.54	0.55 0.55 0.65	0.51 0.41 0.75
B Color Airphotos	0.85 0.52 0.60	0.41 0.67 0.47	0.53 0.57 0.75	0.21 0.33 0.31
C Recorder Tapes	0.03 0.02 0.02	0.02 0.02 0.02	0.01 0.01 0.01	0.01 0.01 0.01

ANOV Table

Source	d.f.	Sum of Squares	Mean Squares	Variance Ratio	$F_{(0.05)}$	Concl.
Workers (W)	3	0.103	0.034	3.668	3.01	S
Methods (M)	2	2.098	1.049			
C_1	1	0.00004	0.00004	0.0001	5.99	NS
C_2	1	2.098	2.098	58.036	5.99	S
W x M	6	0.217	0.036	3.861	2.51	S
Error	24	0.225	0.009			
Total	35	2.643				

C_1 = between Methods A and B

C_2 = between the mean of Methods A and B and Method C

NS = non-significant variance

S = significant variance

TABLE 11

SUMMARY OF ANALYSIS OF VARIANCE FOR

TOTAL DATA REDUCTION TIME

Reduction Time (Minutes per Vehicle)

Workers / Methods	J	R	H	D
A B. and W. Airphotos	5.9 5.2 4.7	4.9 4.3 3.5	5.0 3.9 3.9	3.6 2.9 4.2
B Color Airphotos	5.9 4.7 5.1	4.4 3.9 3.7	4.9 4.2 4.7	4.4 4.8 4.2
C Recorder Tapes	1.5 1.4 1.3	1.3 1.1 1.1	1.1 1.1 0.9	1.2 1.0 1.1

ANOV Table

Source	d.f.	Sum of Squares	Mean Squares	Variance Ratio	$F_{(0.05)}$	Concl.
Workers (W)	3	4.703	1.568	7.659	3.01	S
Methods (M)	2	86.374	43.187			
C_1	1	0.350	0.350	0.924	5.99	NS
C_2	1	86.023	86.023	226.873	5.99	S
W x M	6	2.275	0.379	1.852	2.51	NS
Error	24	4.913	0.205			
Total	35	98.266				

C_1 = between Methods A and B

C_2 = between the mean of Methods A and B and Method C

NS = non-significant variance

S = significant variance

Accuracy of Measurements

To determine the accuracy of speed, volume and headway measurements for the various reduction techniques, each set of tabulated data was checked by a worker other than the one who took the initial measurements. The errors were noted as a fraction of the total number of values recorded. The resulting average percent errors are tabulated in Table 12.

Although the data available were not considered sufficient to permit a formal analysis of variance of the mean percent errors, it appears that the graphic recorder tapes are less prone to measurement errors than the time-lapse aerial photography. There was relatively little difference between the black and white and the color photos' susceptibility to mistakes. In addition, time headway determinations from the recorder tapes and speeds from the aerial exposures tended to be in error the most frequently. This was undoubtedly due to the greater number of measurement and arithmetic maneuvers required in obtaining these quantities.

Comparable information on the accuracy of the Sonne reduction techniques is not available. However, a 96 to 98% reproducibility of measurements to 0.0001 inch has been claimed in the literature (84).

TABLE 12.

COMPARATIVE ACCURACY OF DATA REDUCTION METHODS

Mean Percent Error

METHODS →	Black and White Photography		Color Photography		Graphical Tape	
WORKERS	Aerial Speeds	Headways	Aerial Speeds	Headways	Speeds	Headways
J	9.4%	5.5%	13.9%	1.3%	1.6%	19.2%
R	24.5	1.4	22.4	11.9	8.0	11.2
H	9.6	5.2	18.1	7.8	5.7	2.4
D	14.0	3.0	44.0	6.9	1.6	5.6
Mean of the means	14.4	3.8	24.6	7.0	4.2	9.6

The following criteria were used for declaring a measurement value in error:

<u>Aerial Photographs - Error Ranges</u>

Vehicle travel distance (D_t) as measured on photos in inches: $D_t' - 0.1'' > \underline{D_t'} > D_t' + 0.1''$*

Distance headway (h) as measured on photos in inches: $h' - 0.05'' > \underline{h'} > h' + 0.05''$

<u>Graphical Tapes - Error Ranges</u>

Vehicle travel time (t) as measured on tapes in seconds: $t - 0.05$ sec.$> \underline{t} > t + 0.05$ sec.

Time headway (h_t) as measured on tapes in seconds: $h_t - 0.1$ sec.$> \underline{h_t} > h_t + 0.01$ sec.

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* The underlined symbols refer to initial measurements and the remaining symbols represent the true measurement values.

Problems and Limitations

Many problems unique to each method were observed during the data reduction phase of the research. The student workers were instructed to note any difficulties they encountered and their comments form the basis for the following discussion.

The time-lapse aerial photographs were beset with measurement problems. In addition, to "losing" vehicles under bridges, the pronounced tree and building shadows of the late afternoon often complicated vehicle identification and impaired the measurement precision. Similarly, on routes running East-West shadows cast by the vehicles themselves rendered measurements to the darkened bumpers difficult to obtain. Shadowed vehicles were only slightly more distinct on the color transparencies than on black and white prints.

Most of the workers found a small magnifying glass helpful in identifying vehicles and measuring distances on the photos. However, several complained of eye strain and attributed it to the optical distortions in the lens. Tiring of the eyes was also reported following a prolonged viewing of the color transparencies on a light table.

All of the workers admitted being distracted by the roadside culture depicted on the photos (e.g. a large outdoor swimming pool adjacent to the Tri-State Expressway), and each found the judgments required in deciding questionable cases of vehicle type or lane usage to be time consuming. The failure

of the vehicles comprising a headway pair to appear in the same exposure caused considerable confusion until a means for estimating this quantity had been devised (see Appendix C). The individual black and white prints were somewhat cumbersome to work with and required tedious orientation before measurements could be made. Considerable care was required when measuring distances on the photographs so as to avoid distortions due to parallax; the safest procedure being to measure only between points on or very near the ground. For many of the above reasons, it took slightly longer to gain proficiency at reducing data from the photographs than from the graphic tapes.

Although there was no strip photography included in this study, it can be reasonably assumed that most of the data reduction problems typical of standard aerial photography would be common to Sonne photography. A major exception is the strip photo's freedom from time consuming print orientation.

Each of the workers found it relatively easy to identify vehicles on the Esterline Angus graphic tapes and experienced little difficulty in reducing the desired data. However, there was near unanimity in their opposition to the tedious, boring nature of the task as compared to the aerial photo technique. In addition, confusion occasionally resulted from the failure of a vehicle to be detected by both tube sensors in the travel lane.

CONCLUSIONS

Having described and compared in some detail the characteristics of the pneumatic tube-graphic recorder and various aerial photographic techniques for surveying traffic flow patterns, it is perhaps appropriate to conclude with a recapitulation of the major advantages and disadvantages of each method.

The aerial photographic methods proved capable of effectively detecting and recording the basic traffic flow elements of speed, volume and headway. In obtaining a wide variety of additional data, the time-lapse aerial photo technique, when adapted to a specific survey's requirements, would appear to be particularly useful. Such physical characteristics as vehicle classification and roadway geometry and condition are readily and permanently recorded by the photographic method. Since time-lapse aerial photographs afford a "view" of a vehicle's movement over both space and time, the combined physical and psychological phenomena in traffic flow may be studied in terms of traffic density; acceleration and deceleration practices; passing behavior; lateral placement; spacing habits; and merging, diverging and weaving patterns. This attribute of intermittent photography may become a disadvantage if it is the purpose of the study to collect data under homogeneous highway and environmental conditions. A

possible remedy would be "limited space" photography in which a relatively short, homogeneous section of roadway is filmed from a tower, helicopter, blimp or captive balloon mounted camera.

Among the most important assets of the aerial photographic technique is its ability to pictorially and permanently record the environment in which traffic data is obtained. This attribute enhances the value of the data by affording the investigator with possible reasons for unusual traffic behavior.

The use of aerial photography is impeded by the necessity of having daylight, good flying weather, and an absence of major obstructions to the vertical view. In addition, the cost of collecting and reducing basic traffic data from the aerial exposures is considerably greater than with conventional ground techniques in all but the most complex and extensive surveys.

Color photography yields, in the greatest detail, a complete view of the study route, its vehicles, and the surrounding culture. The advantages over black and white prints usually do not, however, justify its additional cost.

Sonne continuous strip photography shares most of the advantages and disadvantages of intermittent aerial photography. However, its continuous strip format is instrumental in speeding up the reduction of data relative to the pedestrian rate associated with time-lapse photography. But the method requires specialized camera and viewing equipment, and the resulting costs are well in excess of the detector tube-pen recorder system's.

Although the continuous strip technique is subject to the same weather limitations as standard aerial coverage, the Sonne camera's shutterless aperture permits the film to register images under light conditions inadequate for time-lapse photography. Offsetting this advantage, however, is the strip photo's inability to repeatedly record the behavior of an individual driver and his vehicle as they progress along the highway.

The automatic ground technique, as personified by the multi-pen recorder-tube detector system, was found to be a rapid, efficient and accurate means of obtaining speed, volume and time headway data at a fixed location for a limited number of study sites. The method is particularly effective on two-lane routes of light to moderate volumes but tends to yield complex and confusing data records when used on multilane facilities or at periods of congested flow.

Fixed ground devices are limited in their application to the study of traffic flow by an inability to view driver behavior over space as well as time. Thus, pertinent data on passing, merging, diverging, weaving, acceleration, and delay characteristics are difficult, if not impossible, to obtain by the stationary ground devices. Likewise, this method does not lend itself to the study of traffic patterns at complex urban intersections.

None of the procedures studied was judged to be the "ideal" technique for surveying traffic characteristics. Each

was found to suffer from several practical limitations. Nevertheless, time-lapse aerial photography would appear to afford the traffic engineer with his most valuable tool for investigating many of the more important and complex elements of traffic flow.

RECOMMENDATIONS FOR FURTHER STUDY

It is suspected that this study has only touched upon the potential uses of photogrammetric techniques in traffic research. It is, therefore, recommended that the following topics be considered for future projects:

1. The use of a helicopter, blimp or captive balloon for aerial photographic surveys of driver behavior at complex urban intersections and freeway interchanges.
2. The development of photo viewing, scanning and data readout systems designed specifically for traffic work. Such systems are needed if the photographic methods are to become economically feasible. Consideration should be given to combining data reduction and electronic processing into a single automatic system.
3. A comprehensive aerial photographic study of driver merging, diverging, weaving and passing practices.
4. An investigation of curb and off-street parking turnover with color aerial photography.

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APPENDIX A

SPECIFICATIONS OF THE K-17C AERIAL CAMERA

Means of Operation	- Manual or Electrical (24 volts)
Cycling Time	- Modified for 2 Seconds
Lens Focal Length	- 12" (nominal)
Maximum Aperture	- F/5.0
Area Covered at 10,000'	- 1.42 x 1.42 Miles
Type of Shutter	- Between Lens
Shutter Speeds	- 1/75, 1/150, 1/225
Type of Focal Plane	- Vacuum
Film Magazine	- A-9
Negative Size	- 9" x 9"
Film Load Size	- 9½" x 390'
Number of Exposures per Load	- 490
Intervalometer Used	- B-3B

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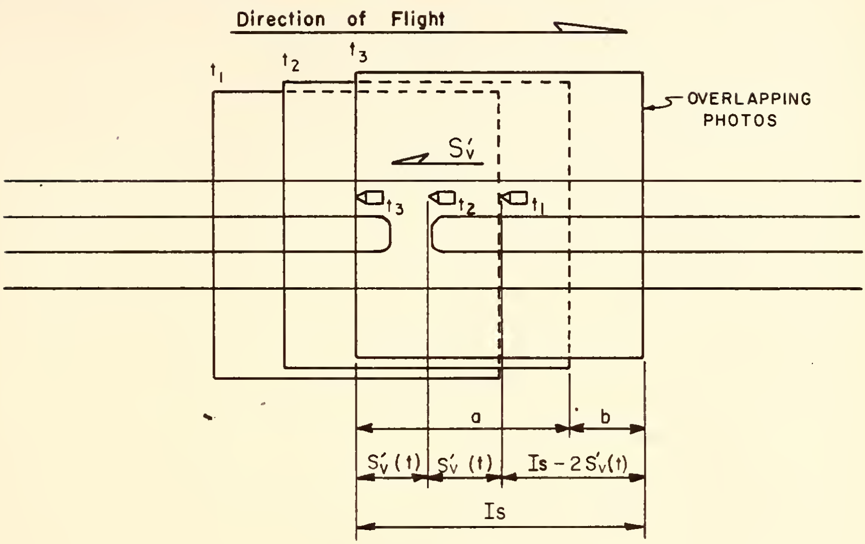
APPENDIX B

DERIVATION OF THE PHOTO OVERLAP EQUATION



$$Q = \frac{a}{Is}(100) = \frac{Is - b}{Is}(100)$$

where a = required overlap

$$b = \frac{Is - 2S_v'(t)}{2}$$

Therefore $$Q = \frac{Is - \left[\frac{Is - 2S_v'(t)}{2}\right]}{Is}(100)$$

or $$Q = \frac{\frac{1}{2}Is + S_v'(t)}{Is}(100)$$

where Q = percent overlap

I = the photographs' dimension parallel to the line of flight, inches

s = scale of photography in feet per inch

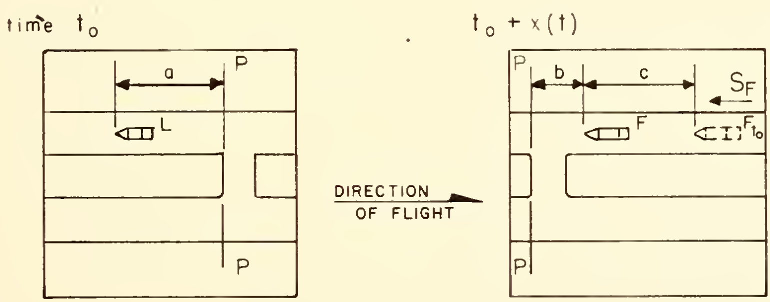
S_v' = maximum expected vehicle speed in feet per second

t = time interval, in seconds, between exposures

APPENDIX C

"BRIDGING" VEHICLE HEADWAY MEASUREMENTS ON TIME-LAPSE AERIAL PHOTOGRAPHS

Occasionally, the two vehicles comprising a headway pair failed to appear on the same photograph. The figures below indicate a method for estimating distance headways by "bridging" the photos in question.



Distance Headway, $h = a + b + c$

$$h = a + b + x(t)S_F$$

where

L = lead vehicle

F = following vehicle

F_{to} = following vehicle at time t_o

t = interval between exposures

x = number of photo intervals "bridged"

PP = a location on the highway common to both photographs

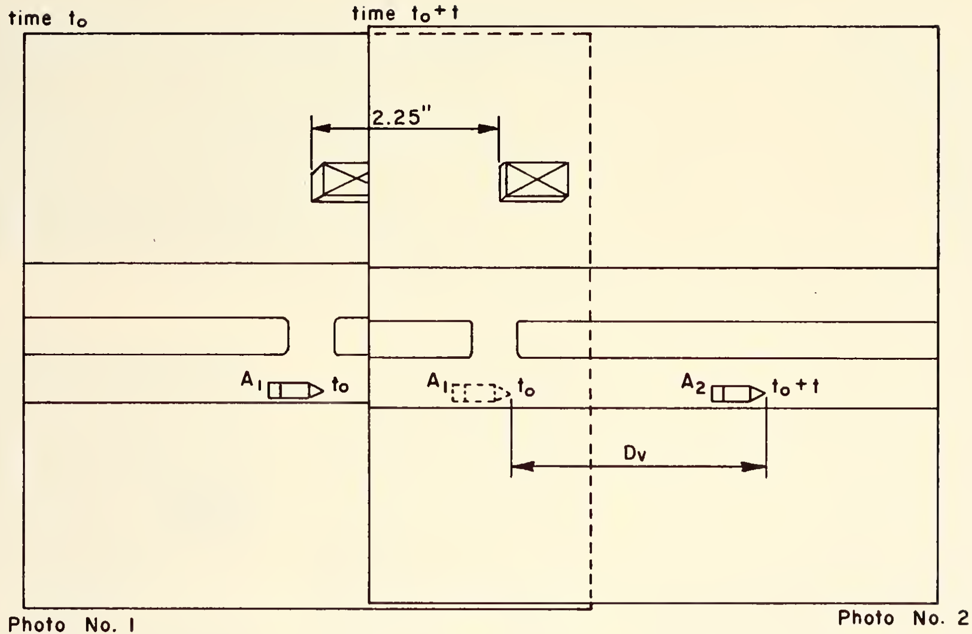
S_F = average speed of vehicle F

STEREOSCOPIC MEASUREMENT OF VEHICLE TRAVEL DISTANCE ON TIME-LAPSE AERIAL PHOTOGRAPHS

The large overlap associated with the time-lapse aerial photography technique affords stereo coverage of the study routes. This characteristic permits the investigator a one-measurement method for determining vehicle speed.

Orienting the photographs as shown in the accompanying Figures 39 and 40, the distance (D_v) that vehicle A moves in the interval between exposures (t) may be found as follows. The fixed photo images, viewed with a lens stereoscope, fuse and are presented in three dimensions. However, moving objects, such as highway vehicles, do not appear in relief but, rather, may be seen in two positions on the roadway (A_1 and A_2). With the photos in stereo, the observer should concentrate on the left-hand image of the vehicle (A_2). Then, using his right hand, the apparent position of vehicle A is marked on the right-hand photo (A_2). This, in effect, locates on Photo No. 1 the position of the vehicle t seconds later than when Photo No. 2 was taken. Distance D_v may then be scaled directly on Photo No. 1.

APPENDIX D



D_V = distance vehicle traveled in time t
t = time interval between exposures

FIGURE 39. ORIENTATION OF AIRPHOTOS FOR STEREO DETERMINATION OF VEHICLE TRAVEL DISTANCE

SCALE: 1" = 150'

FIGURE 40. STEREOSCOPIC PAIR FOR DETERMINATION OF VEHICLE TRAVEL DISTANCE

APPENDIX E

DEFINITION OF STATISTICAL TERMS AND NOTATIONS

Correlation	- the intensity of linear association between two variables.
Level of significance (α)	- the probability of rejecting a hypothesis when it is true.
Population	- the entire collection of observations, measurements or elements of the characteristic in question (for which a statistical conclusion or inference is to be made).
Power of the test	- the probability of rejecting the hypothesis when it is false.
Sample	- any set of observations, measurements or elements selected from a population.
Regression equation	- a function which relates the average value of one variable to the values of one or more other variables.
Sum of squares (SS)	- sum of the squares of the differences between each quantity in a set of observations, measurements or elements and their collective mean.
SSD	- sum of squares associated with deviations from the regression equation.
SSR	- sum of squares associated with the values of the regression equation.

Degrees of freedom (d.f.) - a constant, depending in part upon the sample size, which determines the entry to take in a table of critical values.

LINEAR REGRESSION EQUATIONS BY THE METHOD OF LEAST SQUARES

The estimating linear regression equation is of the form,

$$\hat{Y} = a + b\,X$$

Assuming that the variance of the Y population for each value of X is the same, the best estimate of the regression line is afforded by the method of least squares. This method minimizes

$$\sum(Y - \hat{Y})^2$$

where

Y = observed value of the dependent variable

$\hat{Y}$ = estimated value of the dependent variable

The simple regression equation may be determined as follows:

$$b = \frac{\sum(X - \bar{X})\,(Y - \bar{Y})}{\sum(X - \bar{X})^2} = \frac{\sum XY - n\,\bar{X}\bar{Y}}{\sum X^2 - n(\bar{X})^2}$$

$$a = \bar{Y} - b\,\bar{X}$$

where

$$\bar{Y} = \frac{\sum Y}{n}$$

X = independent variable

$$\bar{X} = \frac{\sum X}{n}$$

n = number of observations

The degree of linear association is indicated by the correlation coefficient (r) and defined mathematically as,

$$r = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 \sum (Y - \bar{Y})^2}}$$

r assumes a range from -1 to +1.

The fraction of the variance in the dependent variable (Y) accounted for by the regression equation is denoted as r^2. A useful equation for computing r^2 directly is:

$$r^2 = \frac{b\,(\sum XY - n\,\bar{Y}\bar{X})}{\sum Y^2 - n\,\bar{Y}^2}$$

A standard F-test is used to determine if the slope (b) of the regression line differs significantly from zero; that is, whether or not Y is linearly related to X. The hypothesis of interest (H) is:

H: $\beta = 0$

with the alternate:

H_1: $\beta \neq 0$

where β is the true slope of the regression line.

The associated analysis of variance table is given below:

Source of Variance	d. f.	SS	MS
Regression	p	$r^2 \sum(Y - \bar{Y})^2$	$\frac{r^2 \sum(Y - \bar{Y})^2}{p}$
Derivations from Regression	n-p-1	$(1-r^2)\sum(Y-\bar{Y})^2$	$\frac{(1-r^2)\sum(Y-\bar{Y})^2}{n-p-1}$

The variance ratio (F_o) is defined by:

$$F_o = \frac{\frac{SSR}{p}}{\frac{SSD}{n-p-1}} = \frac{\frac{r^2 \sum(Y-\bar{Y})^2}{p}}{\frac{(1- r^2)\sum(Y-\bar{Y})^2}{n-p-1}}$$

where

n = number of observations

p = number of independent variables

The associated F-distribution has p and (n-p-1) degrees of freedom (d.f.). In the present research a 0.1 level of significance (α) was used in all regression line tests. This level allowed a 10 percent probability of rejecting a true hypothesis. However, a decreased α level (eg. $\alpha = 0.05$) would have resulted in an undesirably low power of the test by increasing the probability of accepting a false hypothesis.

$F_o > F_{p,\ n-p-1}$	- the slope of the regression line is significant.
$F_o < F_{p,\ n-p-1}$	- the slope of the regression line is not significant.

POISSON DISTRIBUTION OF RANDOM EVENTS APPLIED TO TRAFFIC FLOW

The Poisson distribution, as applied to traffic flow, may be stated as follows (57):

$$p(x) = \frac{e^{-m} m^x}{x!}$$

where

$p(x)$ = probability of x vehicles arriving at a point in time t

m = mean number of vehicles = $\frac{vt}{3600}$

t = given duration of time (seconds)

v = traffic volume (vph)

e = base of Naperian logarithms = 2.71828...

When analyzing the distribution of vehicle headways, the investigator is interested in the probability that no vehicles arrive in a given time interval; that is,

$$p(0) = \frac{e^{-m} m^0}{0!} = e^{-m}$$